SPACECRAFT CHARGING STUDIES IN EUROPE

MULLARD SPACE SCIENCE LABORATORY

UNIVERSITY COLLEGE LONDON

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(6) SPACECRAFT CHARGING STUDIES IN EUROPE.

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20. Abstract

The report reviews European research activities concerned with the electrostatic charging of spacecraft. The contributions of the GEOS and METEOSAT missions are emphasized but many other projects have provided useful information which helps in understanding the potential hazards of charging. The capabilities of European organisations are described and assessed for the contributions they could make in the future.

Recommendation for further work to resolve the outstanding problems revealed by this study are presented.

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SPACECRAFT CHARGING STUDIES IN EUROPE

1. INTRODUCTION

Since the first geosynchronous satellite was launched in 1963 and
the commercial usefulness of that orbit for communications was conclusively
demonstrated, the number of such satellites has steadily increased up to
the present total of about 130. The orbit is now used for other applications,
notably meteorology, and further projects, such as large solar power arrays,
are being planned for the future. The importance of the orbit is therefore
firmly established, and likely to increase in the future. Early in the
history of geosynchronous satellites operational anomalies occurred[28][53]
and remained unexplained until the discovery that spacecraft could charge
up to high voltages was made by DeForest in 1970[22]. Thus it was realised
that the interaction between a spacecraft and the plasma in which it was
immersed could be important to the reliable operation of the spacecraft.
The study of spacecraft charging has created a new working relationship
between the space scientists whose main interest is in the plasma itself
and the engineers whose concern is to build spacecraft that operate reliably.
Progress in this interdisciplinary study of spacecraft charging can be
charted by reference to the proceedings of a series of conferences:-
(i) Sixth ESLAB Symposium on photon and particle interactions with surfaces
in space, Noordwijk, Holland, 1973[1]; (ii) AIAA/AGU symposium of spacecraft
charging by magnetospheric plasma, Washington DC 1975[2]; (iii), (iv) USAF/
NASA Spacecraft Charging Technology Conference Colorado Springs 1976, 1978.[3][8]

The latter concluded with a panel discussion on the theme "The
spacecraft charging hazard - is there a credibility gap?". The fact that
the only answer put forward was "yes" reflects the difficulties in co-
ordinating multi-disciplinary research with different approaches ranging
from the scientific search for knowledge for its own sake to the commercial
concern with economic realities.

The United States Air Force have taken a leading and wide ranging role in sponsoring research into spacecraft charging, through the conferences mentioned above, research contracts, research in their own laboratories and the SCATHA satellite programme. The purpose of this study, also sponsored by the USAF, is to identify the contributions of European organisations to research on spacecraft charging and assess their capability and interest in pursuing the topic in the future.

Bearing in mind the multi-disciplinary nature of the work we have taken the widest possible view of the problem of spacecraft charging and have not restricted ourselves to considering simply the problems of geosynchronous orbit. It remains to be seen to what extent the various fringe topics can contribute to the particular problem, but it is hoped that this report will stimulate the type of cooperation between scientists and engineers which will eliminate any credibility gaps.

SPACECRAFT CHARGING STUDIES IN EUROPE

QUESTIONNAIRE

NAME .... INSTITUTION ....

CO-WORKERS .... NUMBER OF STAFF INVOLVED ....

.... ADDRESS ....

....

....

.... TELEPHONE NUMBER ....

AREA OF PAST AND PRESENT RESEARCH ....

....

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RELEVANT PUBLICATIONS ....

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FUTURE PLANS FOR WORK IN THE FIELD ....

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NAMES AND ADDRESSES OF COLLEAGUES WHOM SHOULD BE CONTACTED

SEPARATELY ....

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I WOULD LIKE TO RECEIVE A COPY OF THE REPORT WHEN IT

IS PUBLISHED   ☐   ✓ or ×

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  ember 15   Holmbury St. Mary, Dorking   (addressed envelope
    1978)   Surrey, England.   attached)

Figure 2.1   Questionnaire format.

2.   METHODS OF INVESTIGATION

The starting point for the study was to send a questionnaire (Fig. 2.1.) to all those scientists who might be able to contribute. The names were obtained through personal contacts, the results of a computer search through the literature and from information supplied on returned questionnaires. The response to the questionnaires was excellent. It provided us with many useful contacts and from follow-up visits and telephone calls we were able to cross-check that we had covered all the active groups.

The computer search was also valuable. The European Space Agency have a large data base at Frascati and our search was carried out from the Department of Industry terminal at St. Mary Cray in England. The key words used in the first scan returned a vast number of references. The total was kept manageable by restricting the keywords and then selecting only the 250 most recent. Of these, approximately half were relevant and they covered both U.S. and European references. Some of the references returned were unlikely to have been uncovered in any other way.

The importance of the two ESA geosynchronous satellite projects GEOS and METEOSAT to this study was obvious from the start. The former was the first scientific satellite to study the ambient plasma at the geosynchronous orbit and therefore much effort was spent to ensure that charging effects, and particularly differential charging effects, were minimised. As a result of its success, GEOS has been able to make more complete observations of the plasma environment at geosynchronous orbit than any previous mission.

METEOSAT, on the other hand, is part of the ESA applications programme in operational meteorology. Its data are collected by remote-sensing optical techniques which are not concerned with the ambient plasma at all. Once in orbit many operational anomalies occurred and they were attributed to spacecraft charging. The resultant data loss was negligible and no

serious damage was caused but it was the only source of operational problems. Considerable effort has been expended since launch in trying to explain exactly how the anomalies occur. The culmination was a test in which the F2 spacecraft, to be flown in a year's time, was irradiated by an electron beam. One of us (ADJ) attended part of the series of tests and was able to observe the discharge from the differential potentials built up on the surface of the satellite through the window of the vacuum chamber; the most convincing evidence of all that arc discharges are caused by electron irradiation. We are grateful to the ESA staff concerned for the assistance we have received with this study.

The report that follows can be split into three main sections. First we review briefly the scientific background of spacecraft charging; where some European activity has contributed to an overall knowledge, we have referred to it. We have not attempted to acknowledge completely the contributions of non-European workers as it would obscure the purpose of this report.

Next we have described the work being done in Europe on each project or under a set of general headings. Finally the active research groups and their particular interests are listed. In this way most of the work should be referred to three times; i.e. under the group responsible, as a research project, and by its relevance to the whole field of study.

3. SCIENTIFIC BACKGROUND

3.1. Spacecraft Charging

The whole of interplanetary space is filled with plasma, a fully-ionised, electrically-neutral, collision-free gas of charged particles. The interaction between the plasma and bodies moving through it is a complex one with many facets. The variety in the types of interactions that can occur is demonstrated by the planets and their satellites in the solar system. The interaction between a spacecraft and a plasma is generally simpler than that associated with the creation of planetary magnetospheres; a shock wave is formed in the plasma and a wake is established behind the spacecraft. The satellite itself acquires an electric charge which changes its potential relative to space. This potential attracts a sheath of charged particles preventing the electric field penetrating more than a short distance into the plasma. Such effects have been known for a long time, from work in laboratory plasmas, well before the first artificial satellites were placed in orbit. Since the spacecraft potential has to be taken into account during the measurement of the plasma parameters it has always been important in scientific studies in space. Recently it has been found that the potentials may reach very large values, particularly in the commercially-important geosynchronous orbit, and charging susceptibility has come to be a significant factor in space design. The maximum potential of the spacecraft is of the order of $V = kT_e/e$ and the sheath thickness is of the order of the Debye length $\lambda_D \simeq 6.9 \sqrt{\dfrac{T_e}{N_e}}$ cm. The relative velocity between the spacecraft and the plasma is much smaller than the electron thermal velocity but is comparable with the positive ion thermal velocity.
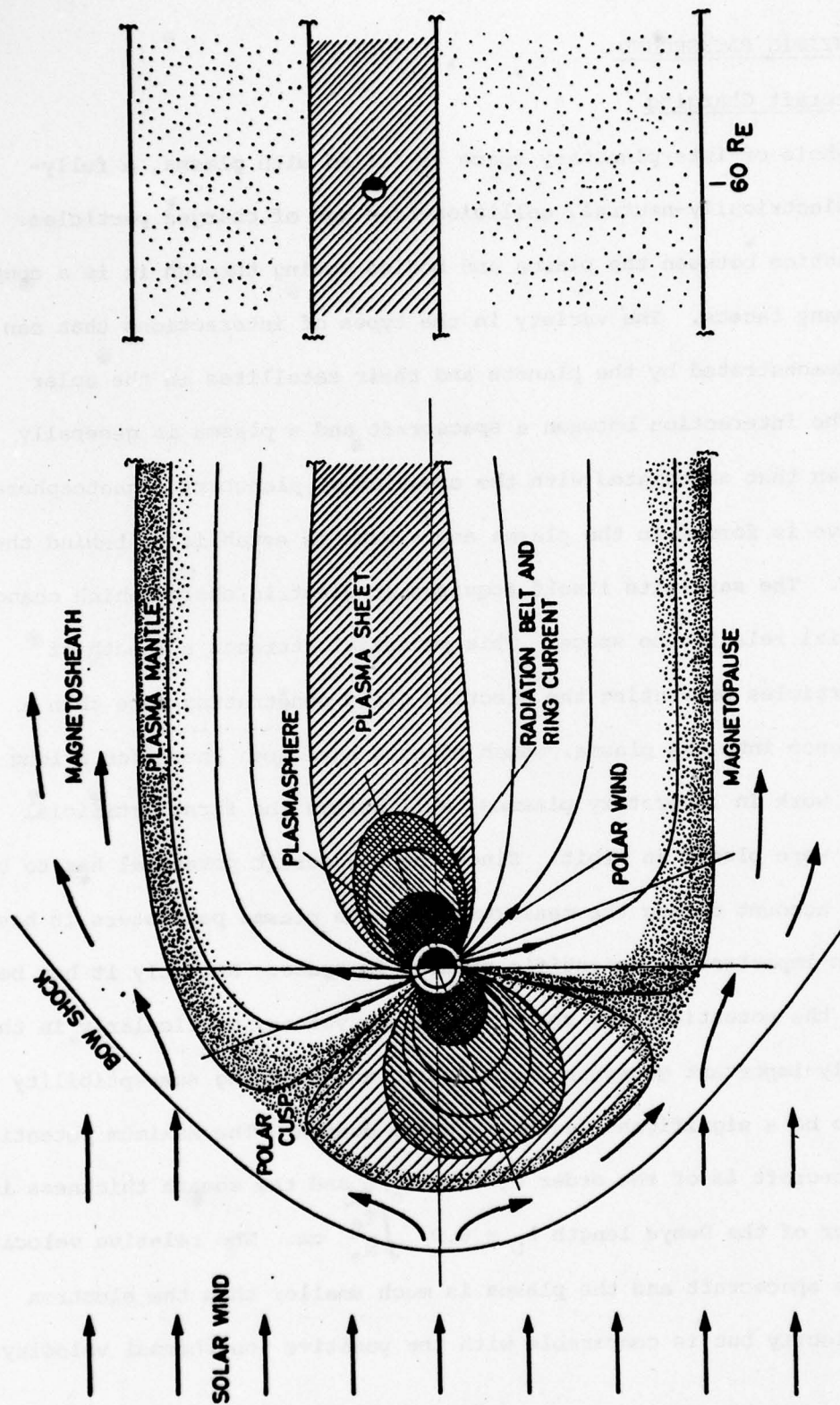
Figure 3.1   Five domains of magnetospheric plasma.
Rosenbauer et al. (68).

3.2. Plasma Environment

Figure 3.1. shows five domains of magnetospheric plasma which could be encountered by an Earth satellite.[14]   The innermost is the plasmasphere which, on average, extends out to the L = 4 magnetic shell.   The plasma is dominated by the cold component with a density ranging from 100 cm^{-3} at the outer boundary to more than 10^5 cm^{-3} in the upper ionosphere.   The electron temperature is in the range $1000^{o}K$ to $5000^{o}K$.   Even though the region may also contain intense fluxes of more energetic particles the latter contributes little to the currents which a satellite would experience.   The boundary of the plasmasphere, where the density drops by two orders of magnitude in a few thousand km, can be found as far out as 7 R_E during magnetically quiet periods but moves rapidly into 2.5 R_E at the beginning of a large magnetic storm.   Its recovery following the storm may take one to two weeks.

The plasmasheet surrounds the plasmasphere and contains the hottest plasma (10^{7} ^{o}K to 10^{8} ^{o}K).   The density is low, (only about 1 cm^{-3}), but because the temperature is high the fluxes can be quite intense.   The plasma density and temperature vary rapidly, particularly during a magnetospheric substorm.   The most intense fluxes are to be found at local times between 2100 and 0600 hr. on magnetic field lines which connect to the auroral zone The fluxes of energetic particles are often highly anisotropic, sometimes with a strongly field-aligned distribution.

The plasma sheet is a very dynamic region and its outer boundary extends many Earth radii down into the geomagnetic tail.   The position and shape of the boundary changes during magnetospheric substorms.

Outside the plasmasheet is the geomagnetic tail whose field lines connect to the polar caps.   The magnetic field lines do not close between north and south hemispheres but extend into the solar wind.   They are unable

to trap plasma, hence the plasma in this region has a lower density (0.1 cm^{-3}) and a temperature comparable with that in the solar wind (10^6 °K).

The solar wind is a well ordered flow of protons with a velocity usually in the range 300 km/s to 800 km/s and a density between 1 cm^{-3} and 20 cm^{-3} at 1 AU. The ion and electron temperatures are of the order of 10^5 °K. The Earth's bow shock converts some of the streaming energy to thermal energy as the solar wind flows around the Earth raising the temperature to 10^6 °K to 10^7 °K in a boundary region termed the magnetosheath.

The plasma regimes around the other planets differ from the Earth's magnetosphere because they have different magnetic structures and atmospheres. The most severe environment for spacecraft charging is likely to be in the Jovian magnetosphere[37] where the trapped electron fluxes are more energetic and more intense but the solar radiation is a factor of 25 smaller.

3.3. Current Balance of a Spacecraft

A satellite immersed in a plasma collects a current of charged particles which depends on its potential V_s with respect to the plasma. The current balance equation is

$$C \, dV_s/dt = \sum_j I_j (V_s, t)$$

where I_j is used to denote the various current components which are described below, C is the capacitance. Under most circumstances the spacecraft is in quasi-static equilibrium and the term on the LHS can be ignored. V_s will then be at a value such that

$$I_e - (I_i + I_{ph} + I_{bs} + I_S \pm I_A) = 0$$

where

I_e = ambient electrons incident on S/C

I_i = ambient ions incident on S/C

I_{ph} = photo-emitted electrons from S/C surface

I_{bs} = electrons backscattered at S/C surface

I_S = secondary electrons emitted at S/C surface

I_A = active emission of electrons or ions from S/C

Since each current component has a different dependence upon V_s and the equation includes some inter-dependencies, it is clear that the solution is complex function of a large number of parameters pertaining to the plasma environment and the surface materials of the spacecraft. Garrett[30] has presented a model formulation in which it is possible to describe the form of each current component.

For example:

$$I_e = N_e \ (8kT_e/\pi m_e)^{\frac{1}{2}} \cdot A \ (1 + eV_s/kT_e)$$

for a satellite of surface area A in an isotropic Maxwellian plasma with concentration N_e and temperature T_e. This immediately establishes the importance of the energy distribution of the particles. If there are departures from an isotropic angular distribution, or a Maxwellian energy spectrum, as can be expected, then the expression becomes more complex.

The low thermal velocity of positive ions makes I_i much smaller than I_e for $V_s \simeq 0$. The velocities of the satellite and the bulk-motion of the ions due to electric fields, can be higher than the thermal velocity and introduce considerable anisotropy in the ion current.

Electrons are emitted from the surface of a satellite in sunlight. The yield depends upon surface characteristics such as the work function but might be $\sim 4 \times 10^{-9}$ A cm^{-2};[56][80] this means that outside the plasmasphere
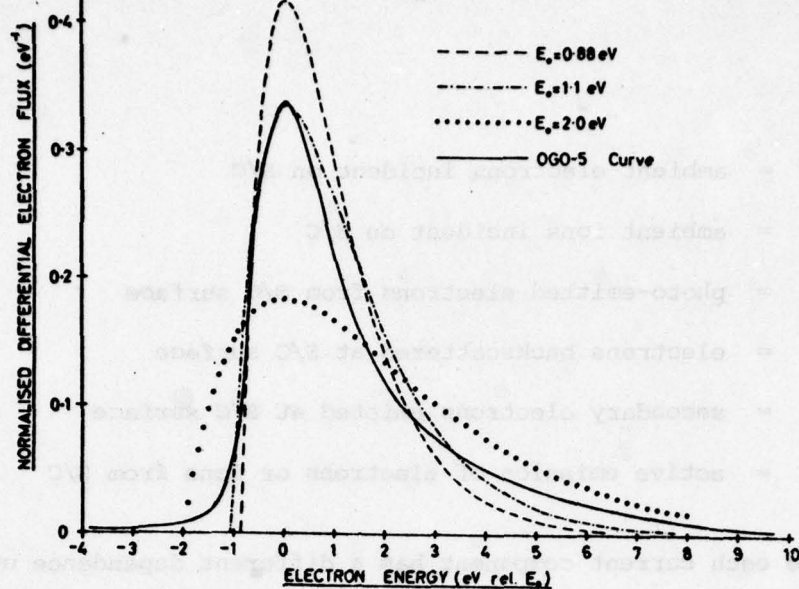
Figure 3.2 — Comparison of experimental energy distribution curve for photoelectrons with three theoretical models. Norman and Freeman (56).

Legend:
- $E_s = 0.88\,eV$
- $E_s = 1.1\,eV$
- $E_s = 2.0\,eV$
- OGO-5 Curve

Axes: NORMALISED DIFFERENTIAL ELECTRON FLUX (eV^{-1}) vs ELECTRON ENERGY (eV rel. E_s)

POLYMER	σ_{max}	E_{pmax}	E_{p1}	E_{p2}
P.T.F.E. (TEFLON)	3.0	300	50	1850
POLYSTYRENE (STYRAFOIL)	3.0	250	30	900
P.E.T. (MELINEX)	3.2	250	30	1200
P.E.T. (MYLAR)	4.8	175	20	850
POLYAMIDE (KAPTON)	2.1	150	30	500

Axes: SEE YIELD $\sigma = i_s / i_p$ vs PRIMARY ELECTRON ENERGY E_p (eV)

Figure 3.3 — Secondary electron yield as a function of incident primary beam energy, for a series of polymer foils. Willis and Skinner (78).

I_{ph} generally exceeds I_e. The energy distribution of the emitted electrons is known to be non-Maxwellian (see Fig. 3.2.). If V_s is positive only those photoelectrons with $E > eV_s$ can escape. When photoemission dominates, V_s goes positive until a current balance is achieved. The asymmetry of this current source obviously tends to cause differential effects between sunlit and shadowed surfaces.

Backscattering of incident electrons effectively reduces I_e by a fraction I_{bs}/I_e which could be as much as 25%. Whilst I_{bs} is a function of the flux and energy of the incident electrons, it is not critically dependent upon V_s.

Secondary electrons are emitted when energetic particles, either electrons or ions, strike a surface. Since they have low energies (less than 20 eV), I_S is strongly dependent upon V_s as for the photoemission current. The yield $\delta(E)$, the number of secondaries per incident primary, is a function of the form
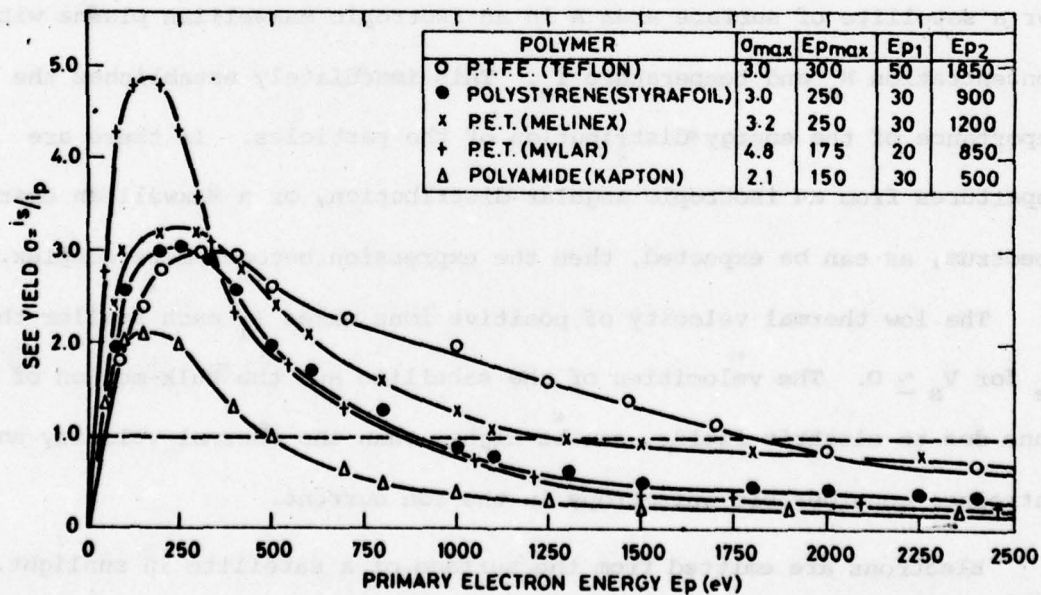
$$\delta(E) = 7.4\ \delta_{max}\ (\frac{E}{E_{max}})\ \exp\ \{-2\ (E/E_{max})^{\frac{1}{2}}\}$$

with a maximum δ_{max} at $E = E_{max}$ (see Fig. 3.3.)[78] $\delta(E)$ depends upon the surface material but in most cases δ_{max} exceeds 1 for a range of energies of a few 100 eV about E_{max}. E_{max} has values in the range 100 eV to 500 eV. Outside the plasmasphere, secondary emission can play a vital role in limiting the extent of surface charging. Consider a non-illuminated surface subject to an intense flux of energetic electrons as encountered in the plasma-sheet, I_e is large and all the other terms are small therefore V_s will increase negatively up to $\sim\ {}^{kT}e/_e$ which could be many kilovolts. As V_s increases the effective energy at which the electrons strike the surface is reduced. If $\delta(E)$ then becomes greater than unity, I_S exceed I_e and the

charging is limited. The secondary emission yield properties of spacecraft surface materials could be the key to charging characteristics of satellites passing through the Earth's shadow and the more hazardous differential effects expected at other times.

I_A represents a controlled emission of electrons or ions[35][36] from an onboard device which can be used to modify the current balance and consequently maintain V_s within acceptable limits. There is a danger that such an operation would increase the disturbance of the local environment but it does provide a means of investigating the influence of V_s on other instrumentation. Active control is expected to find application on large space platforms or missions to the outer planets.

3.4. The Effect of the Various Plasma Regimes on Spacecraft Potential

Within the plasmasphere the dominant current component is I_e, the ambient electron current. Since the temperature in this region is $< 5000^\circ$K the spacecraft potential is usually one volt or so negative. Outside the plasmasphere, and in sunlight, the photoemission current I_{ph} is the largest component, and the potential drifts to a few volts positive. For any isolated element of surface, not in sunlight, the current due to high temperature ambient electrons can dominate and a negative potential of many kilovolts may result. Secondary emission could, however, dramatically counter the effects of the high energy electrons. In an eclipse the whole spacecraft will be subject to charging conditions and floating potentials up to -20 kV have been observed. At solar distances well in excess of 1 AU the reduction in photoemission will accentuate the dominance of the hot electrons and enhance the charging susceptibility.

3.5. Spacecraft Effects

The outer surface of a satellite is generally composed of a large number of elements made of a variety of materials, some conducting, others insulating. They are connected to each other and the basic structure by a host of resistive and capacitative paths. The current balance of each element depends on all the factors noted in the previous section and these internal conductivities. Even the quasi-static current balance approximation can be complicated if the spacecraft is spinning and the element has to respond to changing conditions. Different potentials can be expected over the surface and under some conditions these differences may be large; it would appear that this differential charging presents the real hazard for geosynchronous satellites.

Any non-zero potential will have an influence on some satellite instruments, e.g. low energy particle or electric field sensors and for this reason considerable effort has been made on scientific satellites such as GEOS and ISEE to maximise the area which is conducting and grounded. A more serious problem concerns the danger of discharges or 'arcing'.

The large differences of potential between adjacent elements can be discharged in one of three ways:

(a) There are some regions, for example, a thermal blanket, where two metallic layers are separated by a thin insulator. The inner metallic layer is connected to the spacecraft structure and the outer layer is isolated. The outer layer then charges to a high enough potential to cause breakdown through the dielectric. The discharge punches a tiny hole in the insulator.

(b) The voltage can be discharged across the surface by flashing over a track. This is probably the most common discharge.

(c) The potential can be discharged by field emission at sharp edges or
points.

The first two mechanisms not only cause mechanical damage to the surface
materials but they can also cause electrical faults. At the time of a
discharge, a large current pulse is injected into the spacecraft ground,
and a pulse of high frequency radio noise with strong electric fields is
created. These effects may change logic levels in the electronic circuitry
and inject spurious commands into the system, or in extreme cases may exceed
the allowable voltage on a solid-state device and destroy it. In addition
the RF noise can be conducted around harnesses and generate interference
in numerous sensitive components.

LOW ENERGY PLASMA SENSOR S302
ELECTRON/PROTON SPECTOMETER S321
ELECTRIC DIPOLE S300·9
S310·1
ELECTRIC FIELD PROBE S300·7
ELECTRIC FIELD PROBE S300 8
ION COMPOSITION SENSOR S303
ULF-VLF MAGNETIC SENSOR S300 5
ELECTRON BEAM ELECTRIC FIELD GUNS S329
ELECTRIC FIELD PROBES S300 1-4

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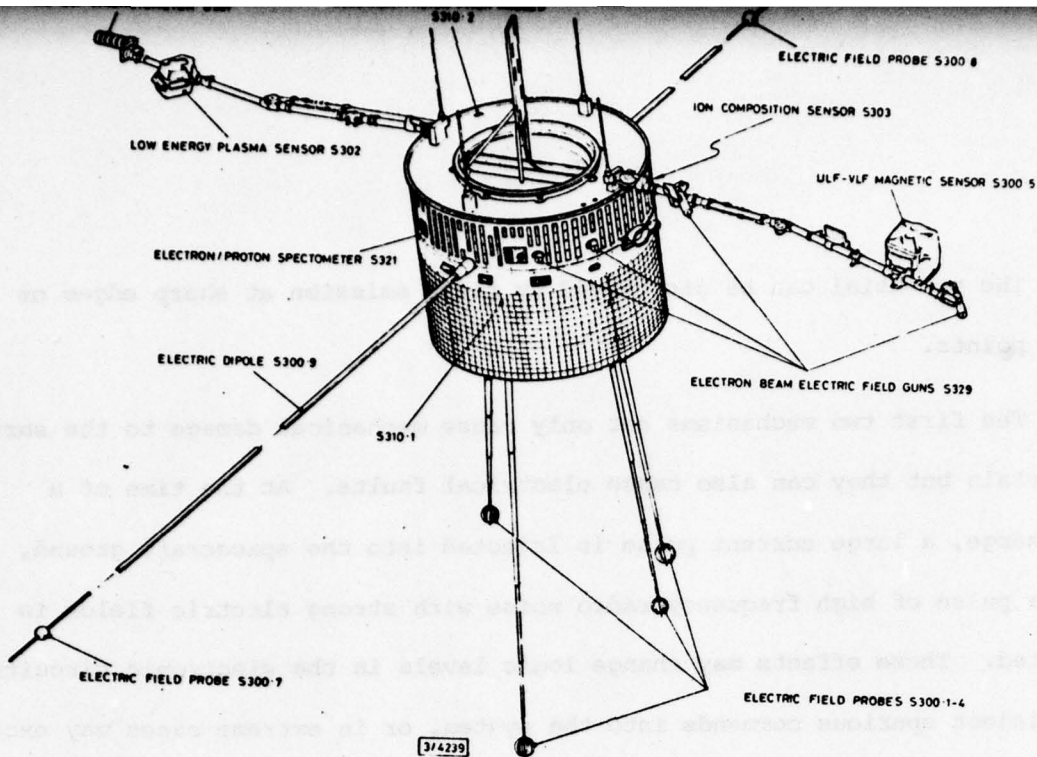
Figure 4.1   Orbital configuration of the GEOS-1 satellite
                    showing the accommodation of the various
                    experiment sensors.   Knott (50).

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• 304
○ 301

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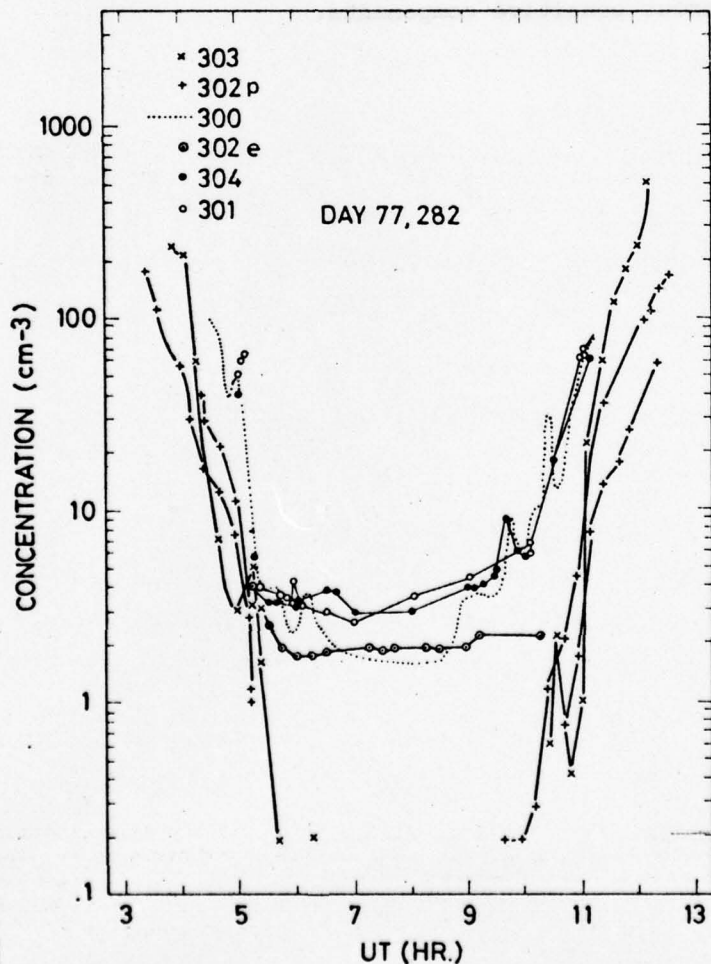
Figure 4.2   Cold plasma density as measured by the five
                    instruments on GEOS-1.   The S303 measurements
                    correspond for the total ion density which was
                    predominantly H$^+$ with only 4% - 12% He$^+$ throughout
                    the pass.   Decreau et al. (21).

4. GEOS AND OTHER SCIENTIFIC SATELLITES

4.1. Description of GEOS

It consists of a cylindrical body (Fig. 4.1.); 1.6m in diameter and 1.1m long, weighing 573 kg at launch. It has a complex set of booms up to 20m in length and is spin-stabilised at 10 rpm. The body-mounted solar cell array generated a power of 115w when first placed in orbit.

Due to a failure in the Delta launch vehicle, GEOS 1 was unable to reach its intended geostationary orbit. It was placed in an elliptical orbit with an apogee of 7 R_E in April 1977. GEOS 2 was successfully placed in a geostationary orbit in July 1978.

The satellites were built for ESA by the STAR Consortium led by British Aerospace of Filton, England. Operations are controlled from ESOC, Darmstadt, Germany where data processing and distribution is carried out. Daily data summaries are made available to all participants in the International Magnetospheric Study.

4.2. GEOS Instrumentation

· GEOS is the first geosynchronous satellite designed purely to make scientific measurements of the plasma environment and for this purpose it carries a comprehensive set of instruments to measure the particle velocity distribution and the electric and magnetic fields.[50] A total of 27 charged particle detectors covers the energy spectrum of electrons (E < 300 keV), and positive ions (E < 2 MeV) with good pitch angle coverage especially in, and near, the loss cone. The mass distribution can be measured for ions of 1 - 140 amu (E < 16 keV). Of particular importance is the fact that five different techniques can be used to study cold plasma (E < 10 eV), enabling

GEOS to provide the first reliable measurements outside the plasmasphere.[21] The presence, or absence of plasma with a temperature less than 10 eV will have a strong influence on whether the spacecraft can charge to high voltages. The techniques are:

(a) the measurement of spacecraft floating potential by the spherical probes on the long radial booms. A negative bias current is injected into the probe from the satellite, forcing the probe to adopt a potential very near to space potential. The potential difference between spacecraft and probe is telemetered to the ground. Knowing the photoemission characteristic of the spheres it has been possible to establish empirical relationships between this potential difference, the spacecraft floating potential, and the plasma density.[57]

(b) the use of a plasma sounder. Part of the booms is used as an antenna to emit pulses of 3 ms duration with frequencies between 0.3 and 77 kHZ. When the sounder frequency is near one of the characteristic frequencies of the plasma a pronounced ringing of the plasma occurs.[25]

(c) the measurement of mutual impedance between various antennas. One pair of booms injects a current into the plasma, with a signal frequency 0.3 - 77 kHZ, and the voltage measured by the long booms is recorded. The plasma impedance peaks at the plasma frequency.

(d) the measurement of suprathermal particle fluxes. Two hemispherical electrostatic analysers, mounted on a short radial boom 1.8m from the satellite surface measure electron and positive ion fluxes in the energy range 0.5 eV to 500 eV. One analyser views parallel to the spin axis; the other at 80° to the spin axis. The analysers are housed in an isolated unit which can be biassed between -28v and +34v with respect to satellite ground.[45]
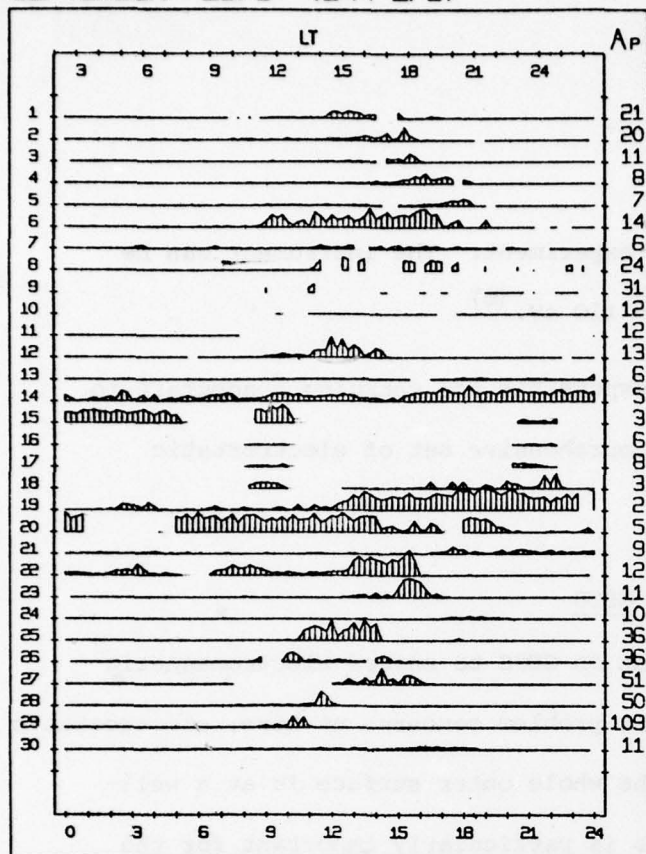
(e) the use of the ion composition experiment. The instrument can be operated in a mode covering 0 - 110 eV. [6]

The energetic plasma fluxes, responsible for charging spacecraft to many kilovolts, are measured by a comprehensive set of electrostatic analysers. [9]
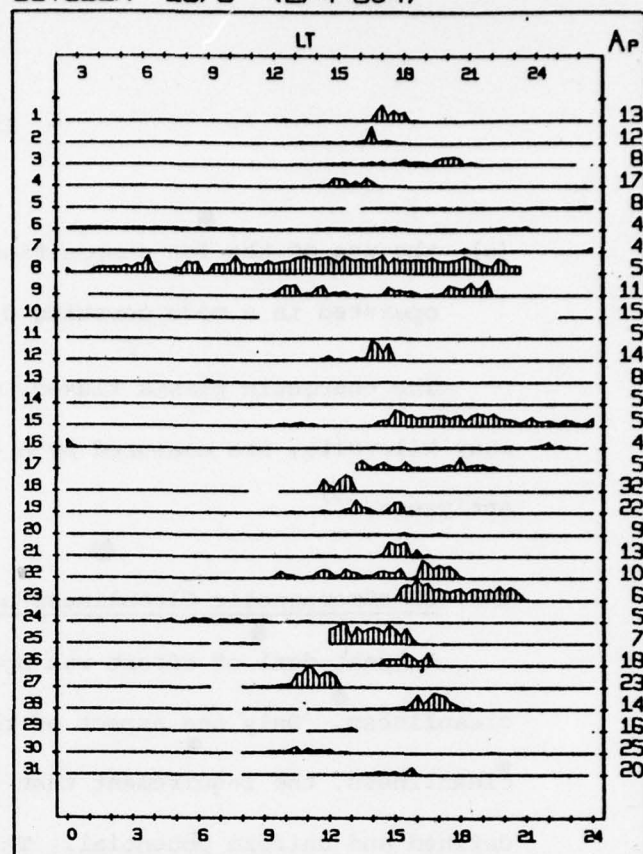
4.3. Electromagnetic Cleanliness of GEOS

A great deal of effort was spent on GEOS to ensure electromagnetic cleanliness. Only one aspect of this problem concerns us here; electrostatic cleanliness, the requirement that the whole outer surface is at a well-defined and uniform potential. This is particularly important for the measurements of cold plasma and electric fields which have high priority in the scientific objectives, partly because of their previous unavailability. In practice it meant that the outer surface had to be conducting and connected to the spacecraft ground. A number of techniques had to be developed to achieve the final result with more than 96% of the exposed surface grounded to the spacecraft structure. [43] The solar cell cover glasses had a coating of Indium Oxide, which only reduced the output of the solar cells by 4%. A conductive black paint (Hughson H322) was obtained and qualified for use on thermal control surfaces. This paint is now being used extensively for the same purpose in the ESA Firewheel project. A technique was developed for grounding reliably the outer surface of Aluminised-Kapton tape used on thermal control surfaces. A new method of testing the conductivity of all the surface elements had to be devised because commercially-available equipment could not operate with currents of 1 nA cm^{-2} and voltages of 0.5v appropriate in this case. While the adoption and qualification of such a high standard of electrostatic cleanliness was costly, it has

Figure 4.3   Cold plasma density profiles from GEOS 2.

UNIVERSAL TIME

NOVEMBER 1978 (305-334)
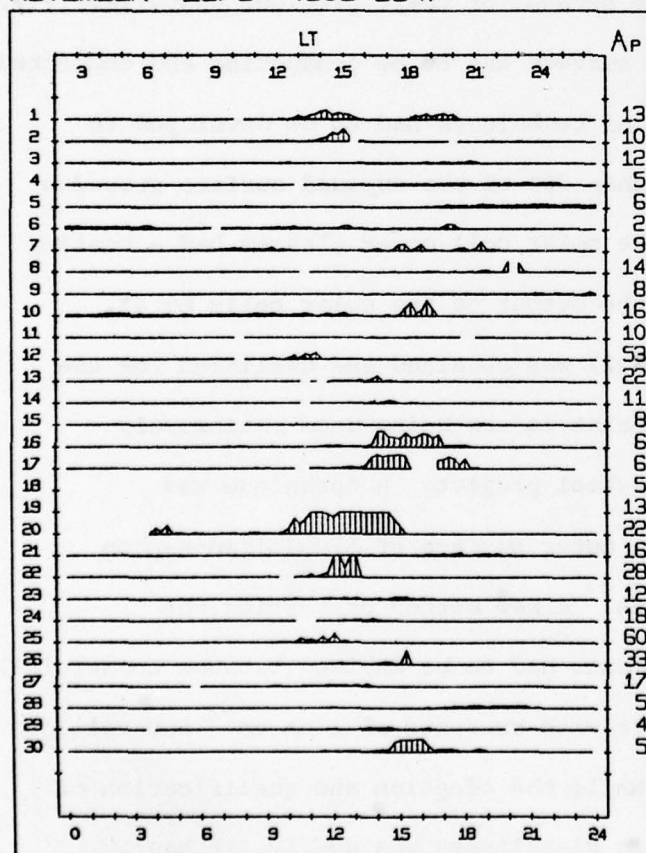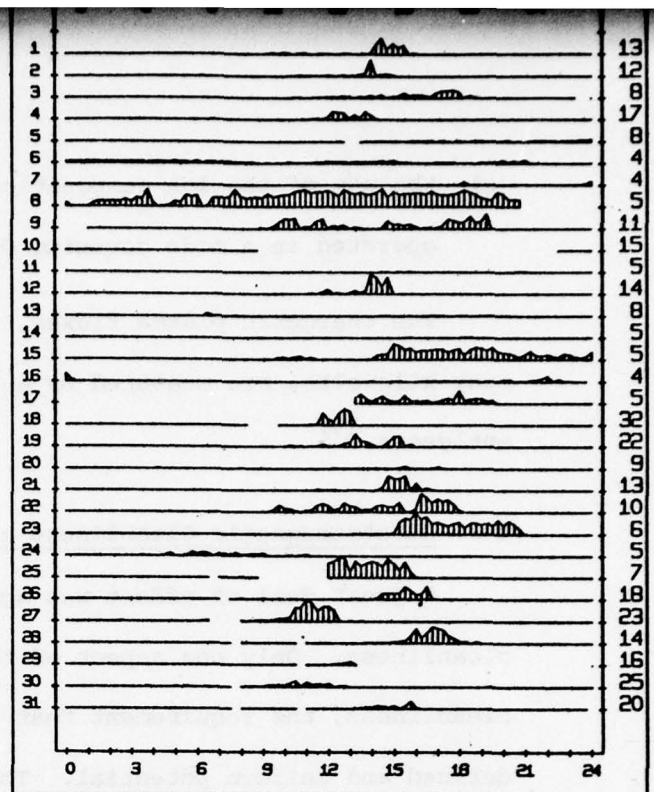
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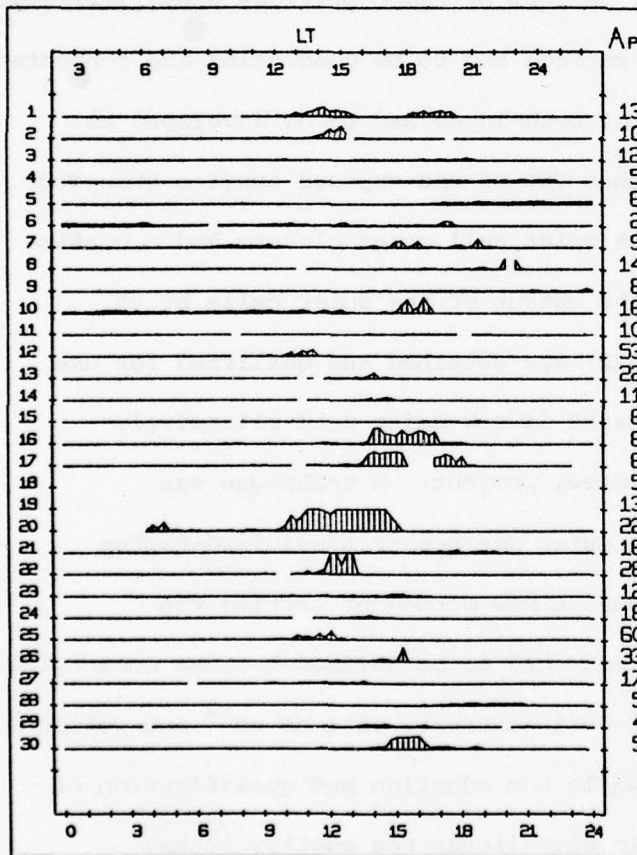
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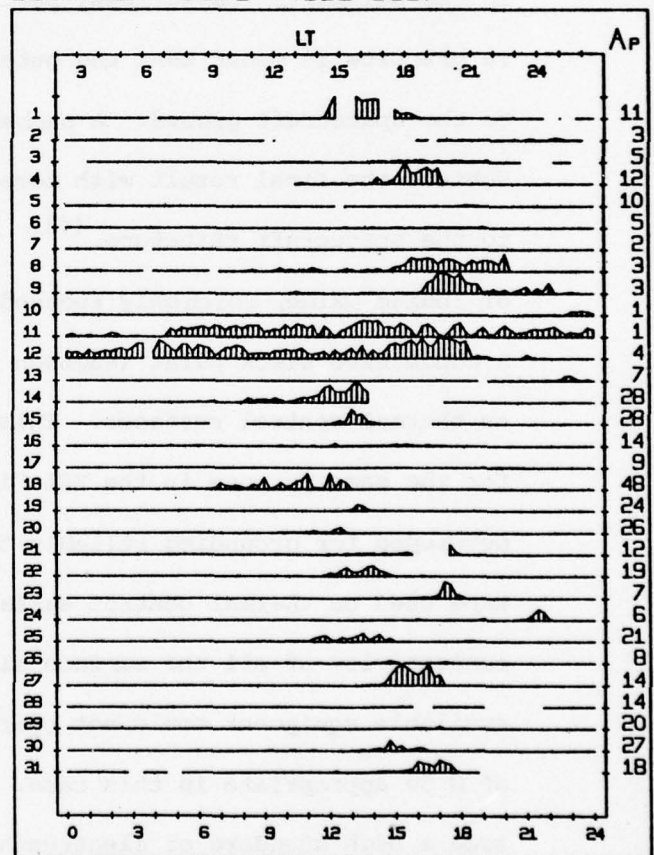
UNIVERSAL TIME

Figure 4.3   Cold plasma density profiles from GEOS 2.
Each daily panel has a scale of 0 - 100 cm^{-3}.

(e) the use of the ion composition experiment. The instrument can be operated in a mode covering 0 - 110 eV.[6]

The energetic plasma fluxes, responsible for charging spacecraft to many kilovolts, are measured by a comprehensive set of electrostatic analysers.[9]

4.3. Electromagnetic Cleanliness of GEOS

A great deal of effort was spent on GEOS to ensure electromagnetic cleanliness. Only one aspect of this problem concerns us here; electrostatic cleanliness, the requirement that the whole outer surface is at a well-defined and uniform potential. This is particularly important for the measurements of cold plasma and electric fields which have high priority in the scientific objectives, partly because of their previous unavailability. In practice it meant that the outer surface had to be conducting and connected to the spacecraft ground. A number of techniques had to be developed to achieve the final result with more than 96% of the exposed surface grounded to the spacecraft structure.[43] The solar cell cover glasses had a coating of Indium Oxide, which only reduced the output of the solar cells by 4%. A conductive black paint (Hughson H322) was obtained and qualified for use on thermal control surfaces. This paint is now being used extensively for the same purpose in the ESA Firewheel project. A technique was developed for grounding reliably the outer surface of Aluminised-Kapton tape used on thermal control surfaces. A new method of testing the conductivity of all the surface elements had to be devised because commercially-available equipment could not operate with currents of 1 nA cm^{-2} and voltages of 0.5v appropriate in this case. While the adoption and qualification of such a high standard of electrostatic cleanliness was costly, it has
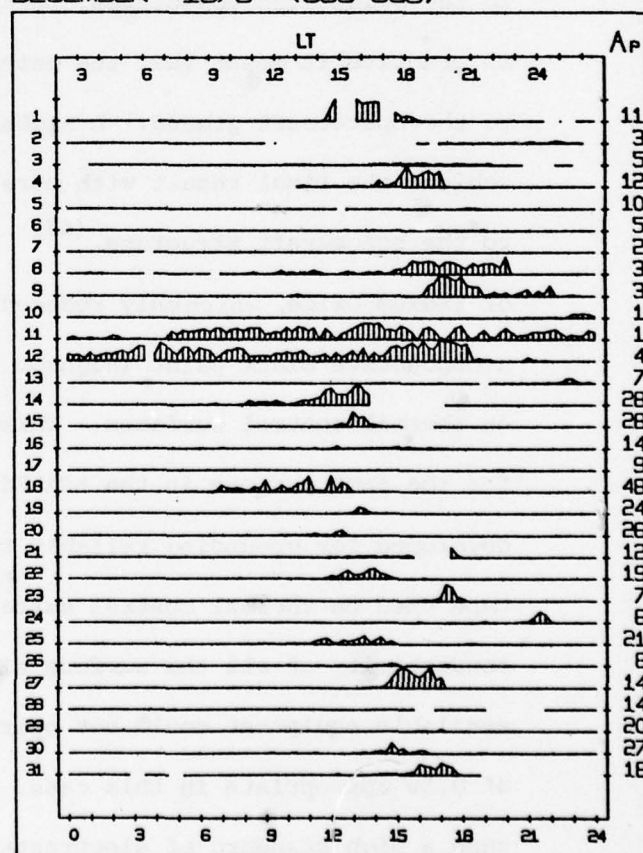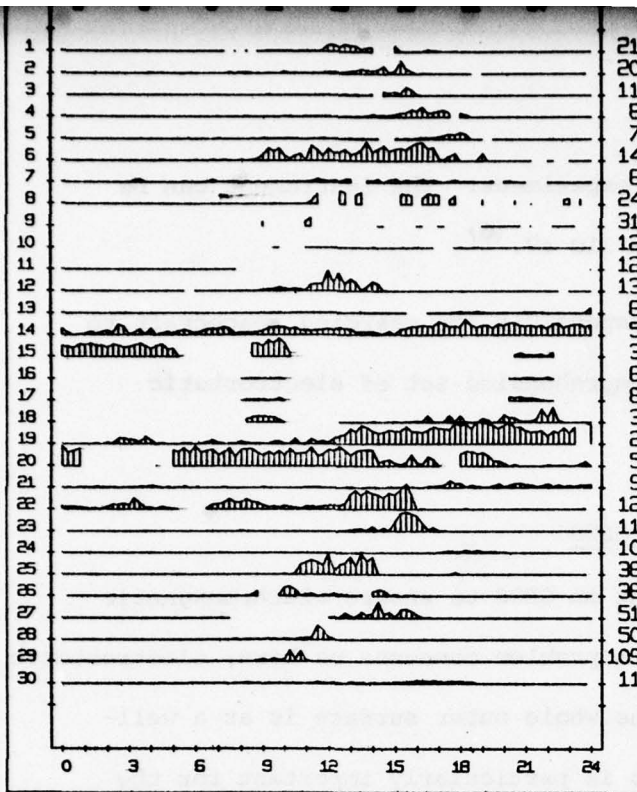
undoubtedly been successful. Now that the materials and techniques have been developed and proven in space, it is a relatively straightforward matter to eliminate differential charging if the initial design of the spacecraft takes the requirement into account.

While the conducting surface prevents differential charging and thus electrical discharges, it does not by itself prevent the spacecraft reaching high negative potentials. GEOS 2 has reached a potential of -1500 volts in eclipse but this is much lower than potentials reached by ATS-5 and ATS-6. It is not known yet whether this is a real difference in behaviour between the spacecraft or is due to differences in the environment.

4.4. Results from GEOS 1 and GEOS 2

The spacecraft potential on both satellites is normally less than 5 volts positive. This is when the spacecraft is sunlit outside the plasmasphere and photoemission dominates the current balance. When GEOS 1, in its elliptical orbit, was in the denser plasma at low altitudes the potential went to a few volts negative. When in eclipse, at high altitudes, both satellites have reached higher negative potentials though it is only in the most recent eclipse season (March 1979) that potentials exceeding one kilovolt have been observed.

There is reasonable agreement between the values of cold plasma density and temperature deduced from measurements using the five different techniques (Fig. 4.2.). The differences are understandable in principle but have not yet been fully explained quantitatively[21]. Figure 4.3. illustrates the variability of the cold plasma density at 6.6 R_E as a function of local time and geomagnetic activity. The general pattern fits existing ideas on the morphology of the plasmasphere and its control by magnetospheric convection. The satellite, GEOS 2, passes through the bulge of the plasmasphere near 1800 LT in magnetically quiet times. During disturbed periods the plasma-
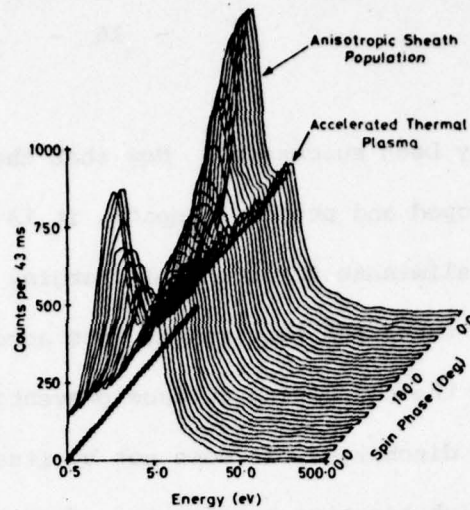
Figure 4.4   A 3-D plot of detector counts as a function of
                energy and sun phase angle.   The photoelectron
                sheath gives a peak in the sun direction.
                Johnson et al. (45).
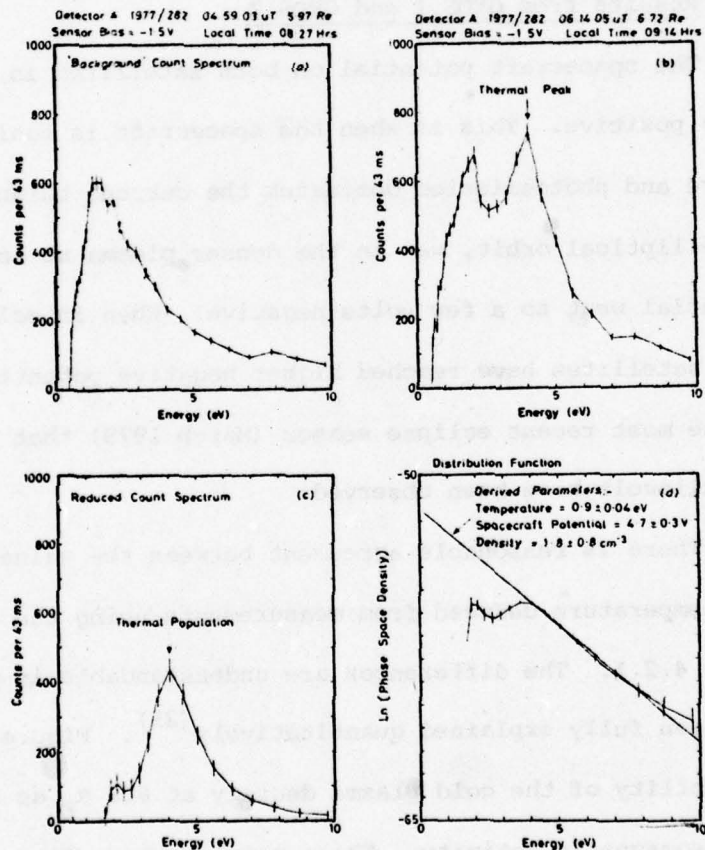
Figure 4.5   A sequence of electron spectra to illustrate the
                sheath subtraction technique.   The spectra are
                (a) photoelectron background (b) raw data
                (c) residual and (d) residual transformed to
                phase space density.   Johnson et al. (45).

pause moves inside the geostationary orbit and no, or very little, cold plasma is seen. It is also apparent that one cannot use magnetic indices to predict reliably when the satellite will be immersed in cold plasma.

Although the suprathermal particle analysers are mounted on a boom 1.7m from the spacecraft surface, they are still within the asymmetric cloud of photoelectrons which surrounds the spacecraft. The photoelectrons hamper observations of the ambient natural plasma and have to be subtracted from total flux measurements. Figure 4.4. shows the photoelectron distribution around GEOS 1 and Figure 4.5. shows how the photoelectron spectrum can be subtracted from the total flux.

The photoelectron distribution was also measured by the UCL Langmuir probe on OGO-5. The distribution was obtained from the probe characteristic in low-density plasma (Fig. 3.2.).

In eclipse the electron cloud around the spacecraft is greatly reduced, but does not completely disappear. The remaining electrons are probably produced by secondary emission which then plays an important part in limiting charge build up, (Fig. 4.6.). Secondary emission effects were also detected by the OGO-5 probe.[56]

4.5. Reference Potential Anomaly

On 5 August 1978 a mysterious failure suddenly occurred on GEOS 2 solar array[47]. It is clear that one end of string of solar cells developed a short circuit to the spacecraft structure. GEOS uses a central starpoint ground isolated from the structure by 330Ω bridged by 0.47 μF; the effect is to shift the 0 volt level, to which the experiments are referenced, to 12 volts positive for approximately one half of each spin period. It appears to the low-energy plasma and wave experiments, that the spacecraft potential is changing by 12 volts. In fact, the anomaly

ENERGY (eV)

ELECTRON DATA
ANALYSER A

DAY 78-039   CBV=+2·3v

21·09·10≊
Sunlight

21·08·26≊
Partial
Sunlight

Eclipse   21·03·23≊

Background 21·03·23

COUNTS IN 43 msec

PLATE VOLTAGE LEVEL
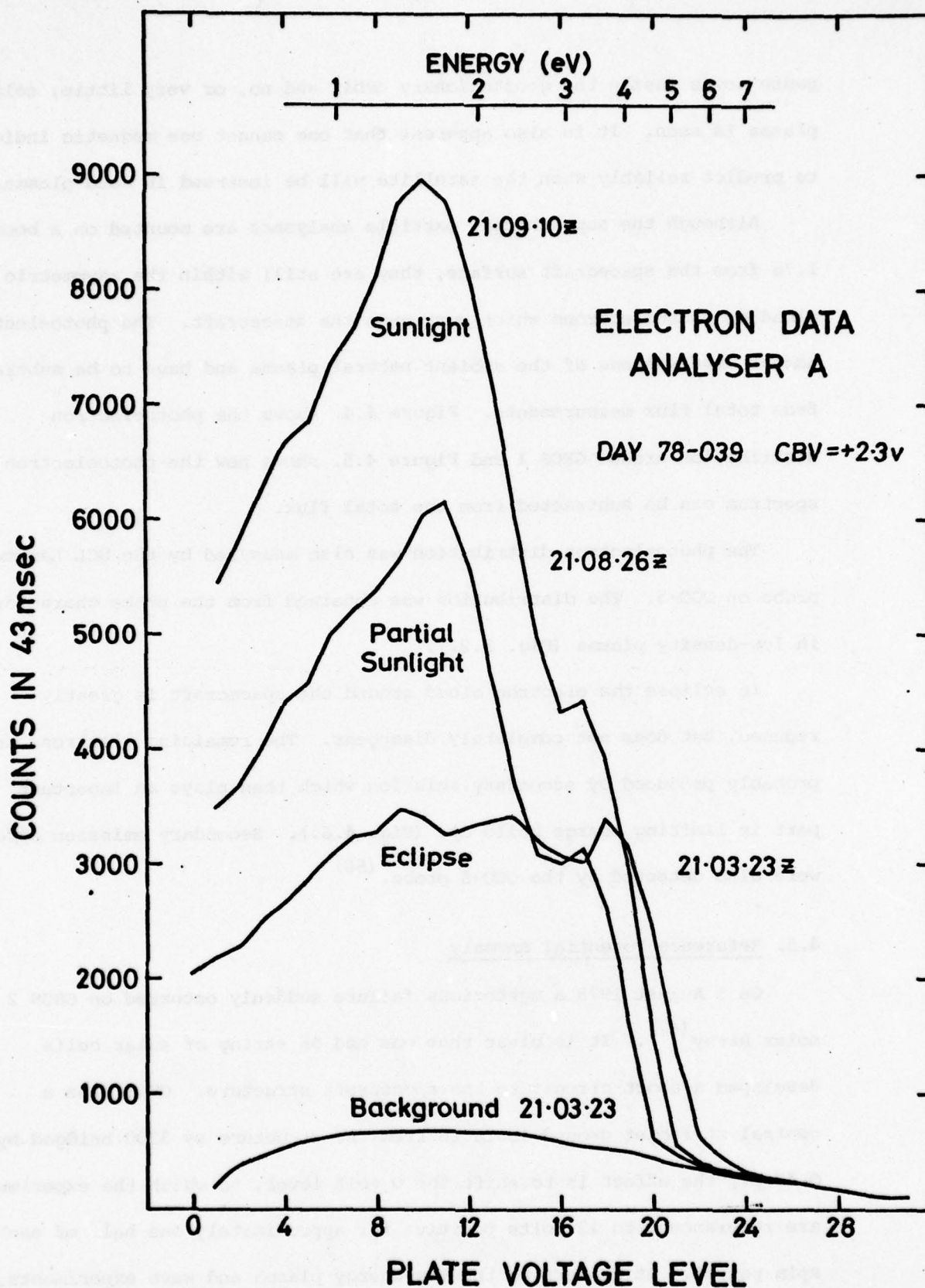
Figure 4.6   Electron spectra from S302 through eclipse. Fluxes
remaining in eclipse are due to secondary emission.

would not have been noticed except for its effect on these instruments.

The anomaly is not related to charging problems and there is no
evidence to suggest that it was in any way due to the conductive coating
used, but it does illustrate the importance of the spacecraft grounding
philosophy which could be a key factor in the susceptibility to charging
effects.

4.6. Other Satellites

ESA, formerly ESRO, have flown a number of ionospheric/magnetospheric
satellites - ESRO 1A, HEOS 1, ESRO 1B, HEOS 2, ESRO 4, ISEE-B. In addition
there have been satellites launched as part of national programmes, e.g.
Ariel, FR1, Helios, Aeros. None of these have direct relevance to spacecraft
charging but, in many cases, the types of instrumentation used for plasma
and particle studies etc. are certainly of interest to some aspects of
charging investigations and are referred to elsewhere in this report.

5. METEOSAT AND OTHER OPERATIONAL SATELLITES

5.1. Operational Anomalies - Statistical Studies

Several European geosynchronous satellites have experienced operational anomalies which could have been caused by electrical discharges. They include the British Skynet 2B, the French/German Symphonie A and B, and ESA's Meteosat. None of these satellites carried instruments to monitor either the plasma environment or the charge state of the spacecraft. In contrast, other operational satellites such as OTS, have shown no unexplained anomalies. It is not known if this is due to particular spacecraft design features or a relative lack of susceptibility of the on board instrumentation. OTS did carry a transient event monitor to record arc discharges.

The only way the anomalies can be linked empirically with spacecraft charging events is by statistical studies, i.e. do the anomalies have the distribution in local-time expected for charging events, and are they more common at times of strong global magnetic activity when the plasma environment is expected to be more intense and more energetic?

The local-time distribution of the anomalies has been produced for four European spacecraft, Skynet 2B[66], Symphonie A, Symphonie B,[20] and Meteosat[67]. All the distributions are combined here to produce Table 1.

SKYNET 2B ANOMALIES IN FLIGHT TELEMETRY DATA
* (ATTRIBUTED TO ELECTROMAGNETIC INTERFERENCE WITHIN THE SPACECRAFT)
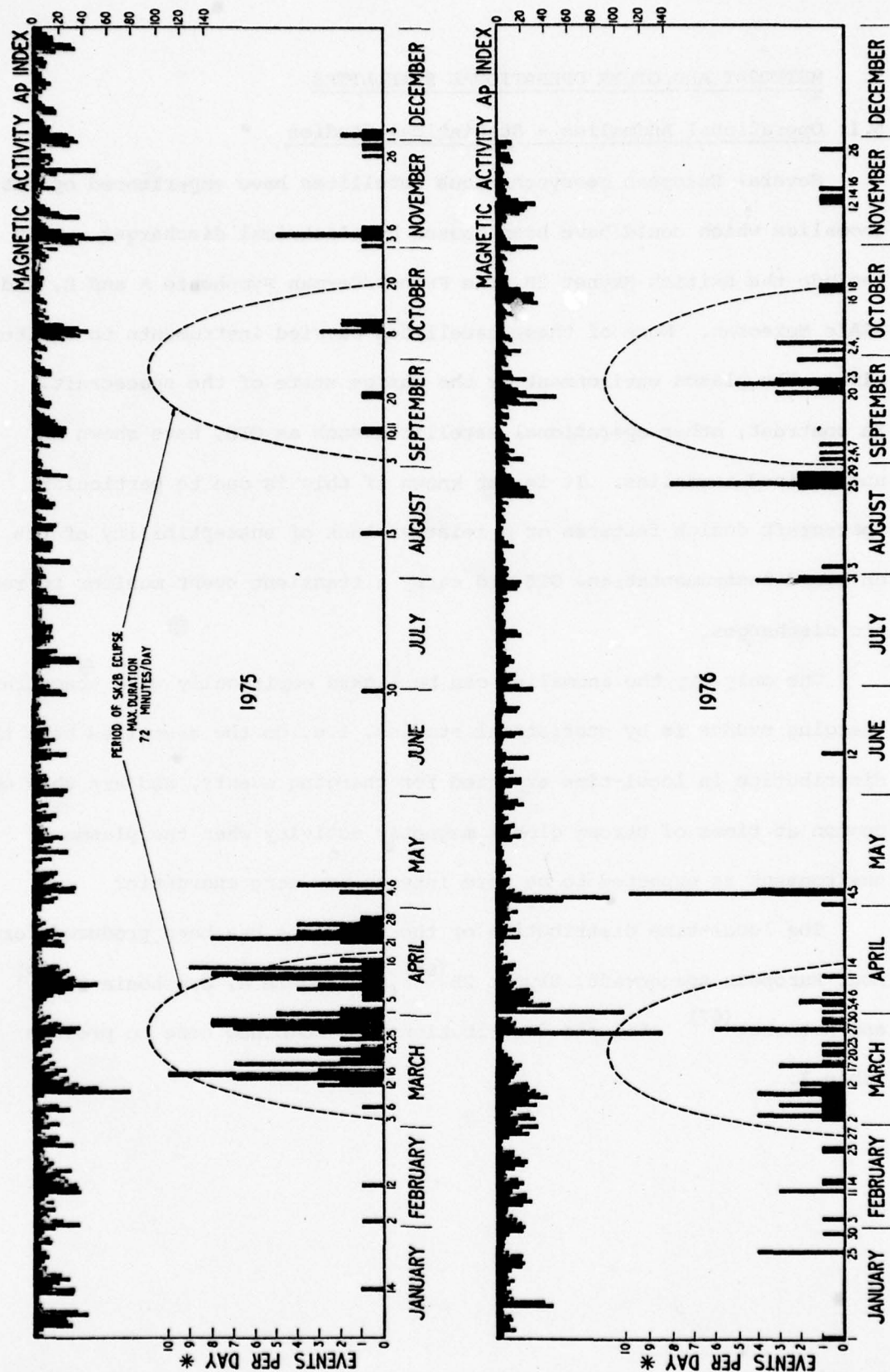
Figure 5.1

TABLE 1

Local time sector	Number of anomalies A	Expected number E	$\frac{(A-E)^2}{E}$
0 - 6	132	122.75	0.70
6 - 12	165	122.75	14.54
12 - 18	96	122.75	5.83
18 - 24	98	122.75	4.99
Total	491		26.06

number of degrees of freedom = 3

reduced χ^2 square = 8.69

probability that the observed distribution would occur randomly from a uniform distribution is less than 0.1%.

Three of the spacecraft distributions peak in the same local time sector, 6-12 hrs., while the fourth peaks in 0-6 hrs. The distribution, although reasonably consistent for the four spacecraft, is not a strong function. The significance of the distribution is not obvious because the most intense fluxes of energetic particles are seen between 21 hrs. and 3 hrs. local time.

There is a significant correlation with global magnetic activity. Anomalies are more likely during periods when the Earth's magnetic field measured by ground-based magnetometer is more variable. For Skynet 2B[66] (Fig. 5.1.) and Meteosat[67] (Fig. 5.2.) the correlation is strongest with
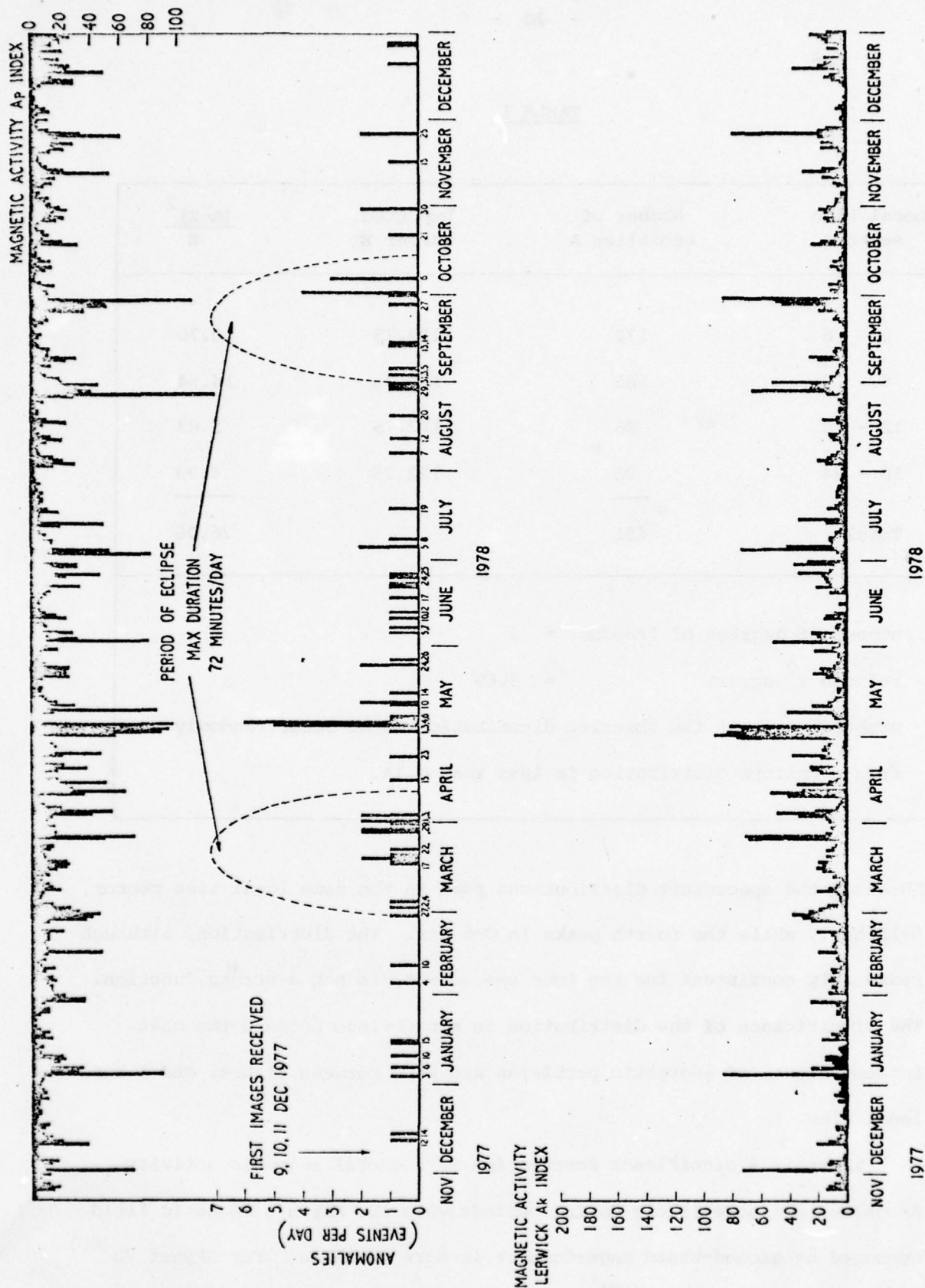
Figure 5.2   Meteosat F1 anomalies attributed to electromagnetic
interference within the spacecraft. Robbins (67)

the level of magnetic activity, as shown by the A_p index, for the day two days before the anomaly occurred. The relation between magnetic activity at the ground, even when measured at an observatory magnetically conjugate with the satellite, and the plasma environment of the satellite is complex and indirect. Magnetospheric substorms cause magnetic disturbances at high latitudes and inject intense particle fluxes into the night-time sector of the magnetosphere, but the magnetic index itself is a very crude indicator of the energetic particle distributions at any instant. However, magnetic indices are produced on a routine basis and they are the only continuous monitors of substorm activity currently available. The fact that there is a statistically significant correlation between the occurrence of anomalies, and geophysical parameters demonstrates that the cause is associated with the environment of the satellite.

GEOS 2 is $2\frac{1}{2}$ hrs. ahead of Meteosat in local time and has data available on the plasma environment but a preliminary comparison between the occurrence of anomalies and the environment at GEOS did not reveal anything significant.[67] The time difference is likely to be important because, in the 0-12 hrs. LT sector, energetic electrons, injected by substorms near midnight, drift eastwards around the Earth and encounter Meteosat before GEOS. The electron drift rate in the magnetic field is proportional to energy and it takes 20 keV electrons, at the upper end of the energy spectrum, 50 mins. to reach GEOS 2 from Meteosat. Even when such delays are taken into consideration there was no obvious change in the plasma environment at GEOS which might have been responsible for an anomaly. The implication is that although the plasma environment is important it is not the only factor involved in producing an anomaly.

5.2. Arcing Tests on Spacecraft

It is necessary to establish that electric discharges on the spacecraft
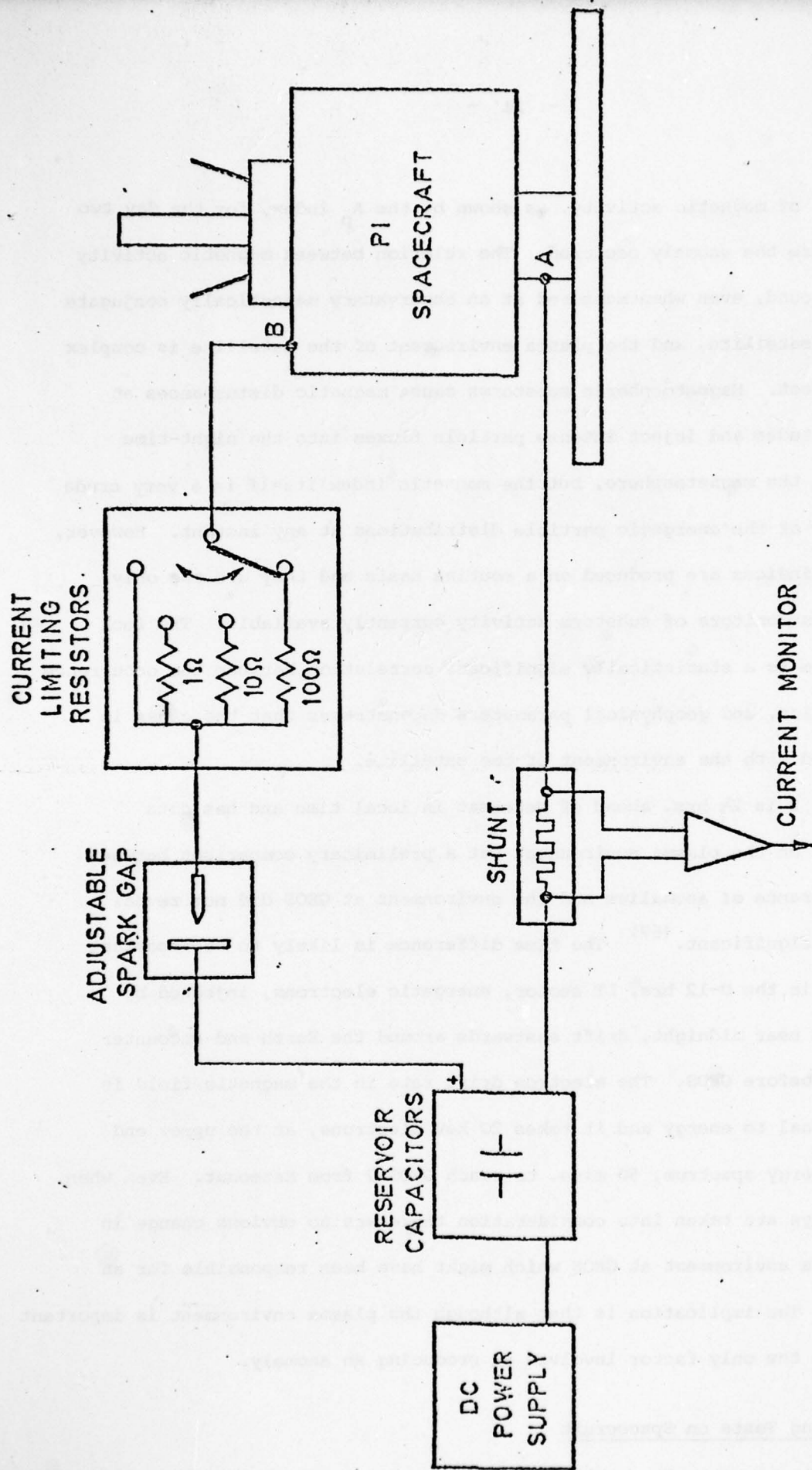
Figure 5.3   Meteosat P1 simulated arcing test layout. Robbins (67)

surface can cause the operational anomalies. The experimental arrangement employed to confirm this on both the Symphonie[20] and Meteosat spacecraft[5] is shown in Fig. 5.3. The spacecraft structure is part of the return circuit for the discharge current from the capacitors. The ground of the spacecraft electrical system is connected to the spacecraft structure. The size of the current transient is controlled by varying either the voltage applied to the capacitor or the magnitude of the current-limiting resistor. For the Meteosat tests the size of the capacitor was comparable with the capacitance of the thermal shields on the ends of the cylindrical body of the spacecraft. The two points of contact with the spacecraft were varied during the series of tests. It was found that the anomalies experienced in flight could be reproduced if the correct injection point was chosen. [67] For example, one of the most common anomalies on Meteosat stopped the radiometer mirror scanning. This could be reproduced if the arc current was injected near the mounting of the radiometer mirror. It was not possible to deduce from these tests exactly where the discharge occurred. It was found that the anomalies which occurred in flight were those with the lowest threshold in the ground tests. The tests on the Symphonie spacecraft were also able to reproduce the flight anomalies. [20]

5.3. Irradiation of Meteosat Components

A series of tests were carried out to find out which surface on Meteosat could charge to high potentials. The principal candidates were the thermal shield on the top and bottom surfaces of the cylindrical body[52] and the radiometer's primary mirror. [67]

The material of the thermal shield was Kapton, 25 microns thick, with an Aluminium layer on both sides. Only the aluminised surface on the

inside was connected electrically to the spacecraft. The outer surface was free to charge when irradiated by energetic electrons. Two samples of the material were irradiated with electrons ranging up to 20 keV energy at currents up to 1.25 nA/cm^2. One sample was made similar to the flight configuration, but the other had most of the outer surface grounded to the spacecraft structure in a way that could be used on subsequent spacecraft. The former charged up to a potential of 1700 volts before the potential was limited by arcing, though arcing was detected near the edges at voltages from 500 volts up to a maximum of 2500 volts. These voltages are much lower than the breakdown voltage for the bulk of the Kapton, demonstrating that the important discharges occur through effects near the edges of the material. The capacitance of the material deduced from the rate at which the voltage increased was comparable with calculated values. Partially grounding the outer surface reduced the discharge current by a factor of 10 and reduced the surface potentials, taking it below the level at which it would affect the spacecraft. The tests enabled the amount of electrical energy that could be stored in the thermal shield to be estimated. The arcs observed on the sample with a floating outer surface could be large enough to cause anomalies in flight.

The results of the irradiation tests on the radiometer mirror are more difficult to interpret.[67] The potential reached by the surface depended on the cleanliness of the entire mirror. Small carbon tracks at the edge were capable of keeping the potential below 50v. When cleared, the mirrors reached potentials of 5 kv without giving rise to arc discharges. When the mirror was charged up to 5 kv in air at room temperature by a low impedance power supply, small discharges occurred near the mounting brackets.
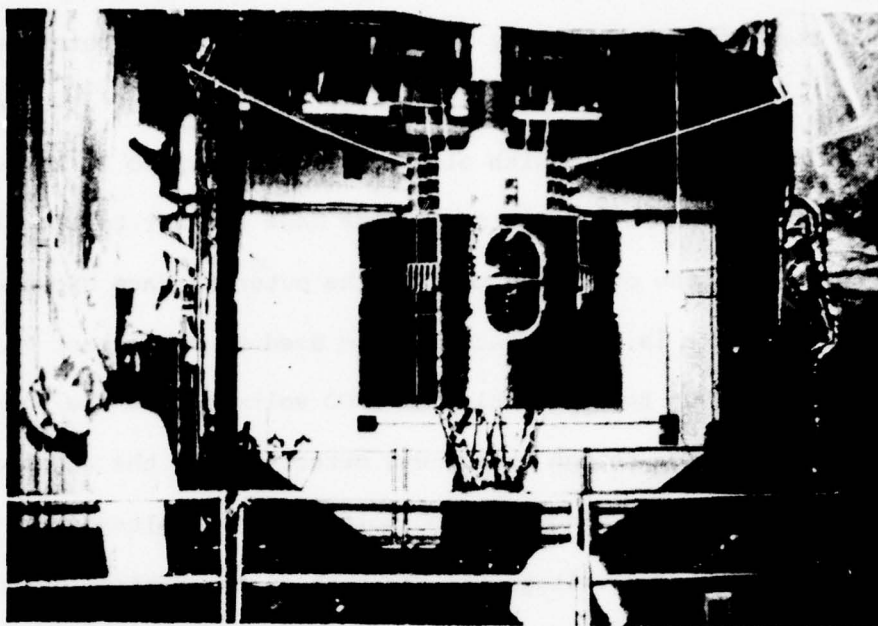
Figure 5.4   Meteosat F2 mounted in SIMLES chamber for irradiation
                    tests.
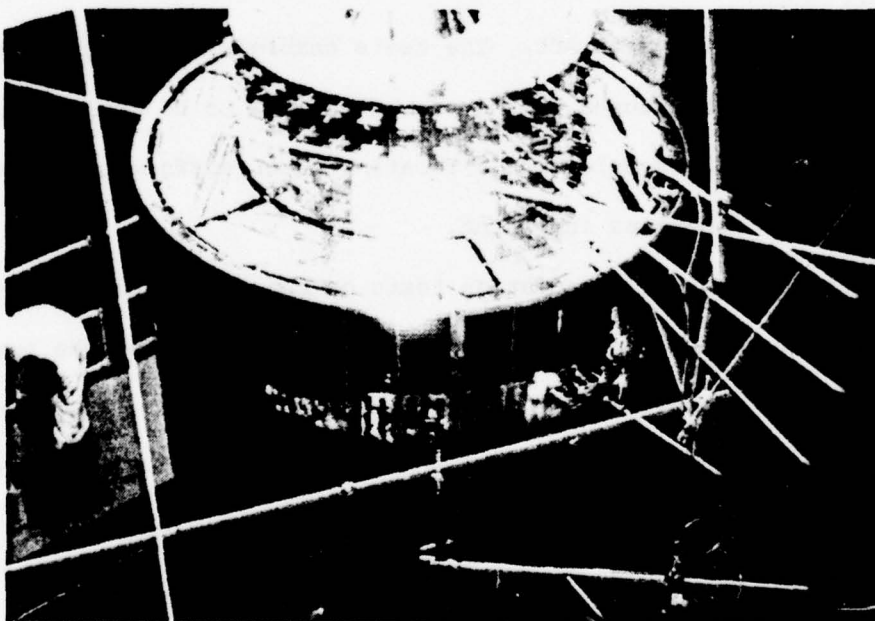
Figure 5.5   Surface potential probes used on Meteosat F2 during
                    tests.

Although the mirror could be charged up to high potentials the results of irradiation depend very much on the actual state of the mirror and the precise configuration of the mounting hardware.

5.4. Irradiation of the Complete Spacecraft

The P1 model of the Meteosat spacecraft was mounted in the SIMLES vacuum chamber at Toulouse (Chapter 8) and irradiated by a broad uniform beam of energetic electrons. The beam was produced by firing an electron gun through an Aluminium diffusing screen 0.75 microns thick. The beam intensity was of the order of $1nA/cm^2$ and essentially uniform over an area greater than the projected area of the spacecraft. The spacecraft was mounted on a spin table, which was itself fixed to a gimballed mounting and could be tilted $\pm 20^{\circ}$ from the vertical (Fig. 5.4.). The surface potential was measured by an array of probes held close to the surface on the opposite side from the beam while the spacecraft was free to rotate underneath (Fig. 5.5.). The electric field of the discharges was detected by an array of five antennae mounted on the base of the chamber. The metal frame of the spacecraft could be isolated from the chamber, or it could be grounded to it to simulate in a crude way the effect of solar illumination in maintaining the potential of the metal structure close to plasma potential. It was not feasible to operate the electrical systems of the spacecraft to detect directly whether any electrical discharges were large enough to cause operational anomalies.

When the spacecraft is irradiated, different surface elements quickly charge up to different potentials. Figure 5.6. shows the surface potential around the equatorial band of the spacecraft as it made one complete revolution. Adjacent surfaces differ in potential by as much as 3 kv. Many discharges occurred and were detected by their rf electric field at

the antennae (Fig. 5.7.) and also as a small blue flash (cover picture) when seen through the window of the vacuum chamber.

However the energy level of the discharges was found to be much less than that required to trigger anomalies in the simulated arcing tests (Section 5.2.). The discharge mechanisms dissipated the stored charge before high energy levels could be built up.

5.5. Delays Between Charging Events and Anomalies

There are some indications that anomalies occur some time after charging events. For example:

(a) although anomalies are more common during the eclipse season for the spacecraft (Figs. 5.1., 5.2.),[66][67] when it is expected to charge to higher potentials, the anomalies do not occur during the eclipse.

(b) the occurrence of anomalies correlates most strongly with magnetic activity two days before (Section 5.1.).

(c) anomalies are most likely in the local time sector 06-12 hrs. (Section 5.1.).

The delays implied by these results range from hours to days. There may, of course, be other explanations for (b) and (c) which do not involve a delay.

The various laboratory tests on Meteosat did not detect any delay in the process. The charging time is given by an expression of the form $C \frac{dV}{dt} = I$ [52] with the charging current I decreasing as the potential of the surface increases. When the potential reaches a threshold, continual discharges prevent the potential rising any higher. This takes only a few minutes. When the charging current is stopped in the laboratory, with no discharging mechanisms like photoemission available, it can take hours for the potential to decay.[52] During the irradiation tests on Meteosat, the potential distribution quickly reached that shown in Fig. 5.6. and
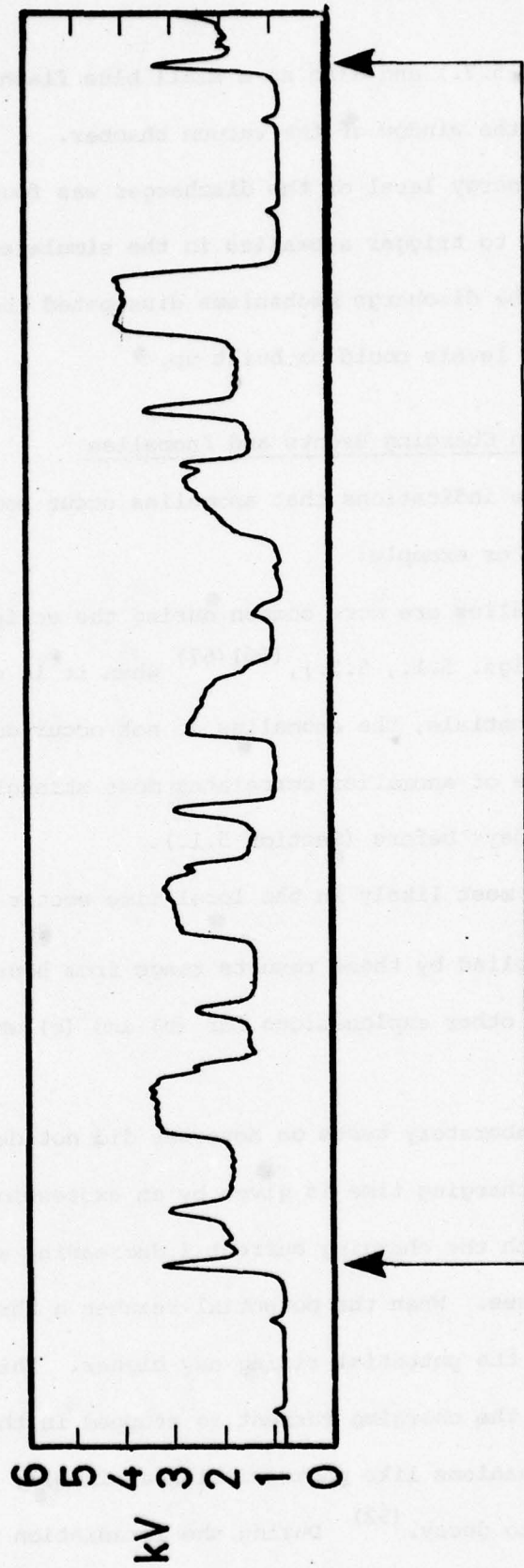
One complete revolution of spacecraft.

Figure 5.6   Surface potential variation around equatorial band.

then remained steady as long as the charging conditions were not changed, although arc discharges occurred all the time.

The time relationship between the charging event and the arc discharge, which causes an anomaly, has not been established. It could well be important in understanding the nature of the whole process.

5.6. Conclusions

The work done on charging effects of the Meteosat spacecraft have established a number of the elements in the casual chain relating spacecraft charging to the operational anomalies. They are:

(1) Anomalies are related to the geophysical environment and probably to energetic plasma.

(2) Arcs can cause the anomalies.

(3) Irradiation by energetic electron fluxes causes differential charging of the spacecraft surface which discharge through arcs.

The strong probability is, therefore, that the flight operational anomalies are caused by spacecraft charging but it has not been conclusively established. The quantitative evidence from the tests suggests that the arcs are not strong enough to cause anomalies and that the discharges are far more common than the anomalies. To counter this, the tests demonstrate that the process is extremely sensitive to the configuration of the space-craft. The sensitivity of the electronic circuits depends on where the arcs occur, and edge effects and mounting hardware control the potentials reached.

It seems that some other factor or factors are involved in generating an anomaly from the discharges - perhaps the coincidence of two or more discharges giving an especially large discharge current, or unusual

100 V/m

.2 µs

0
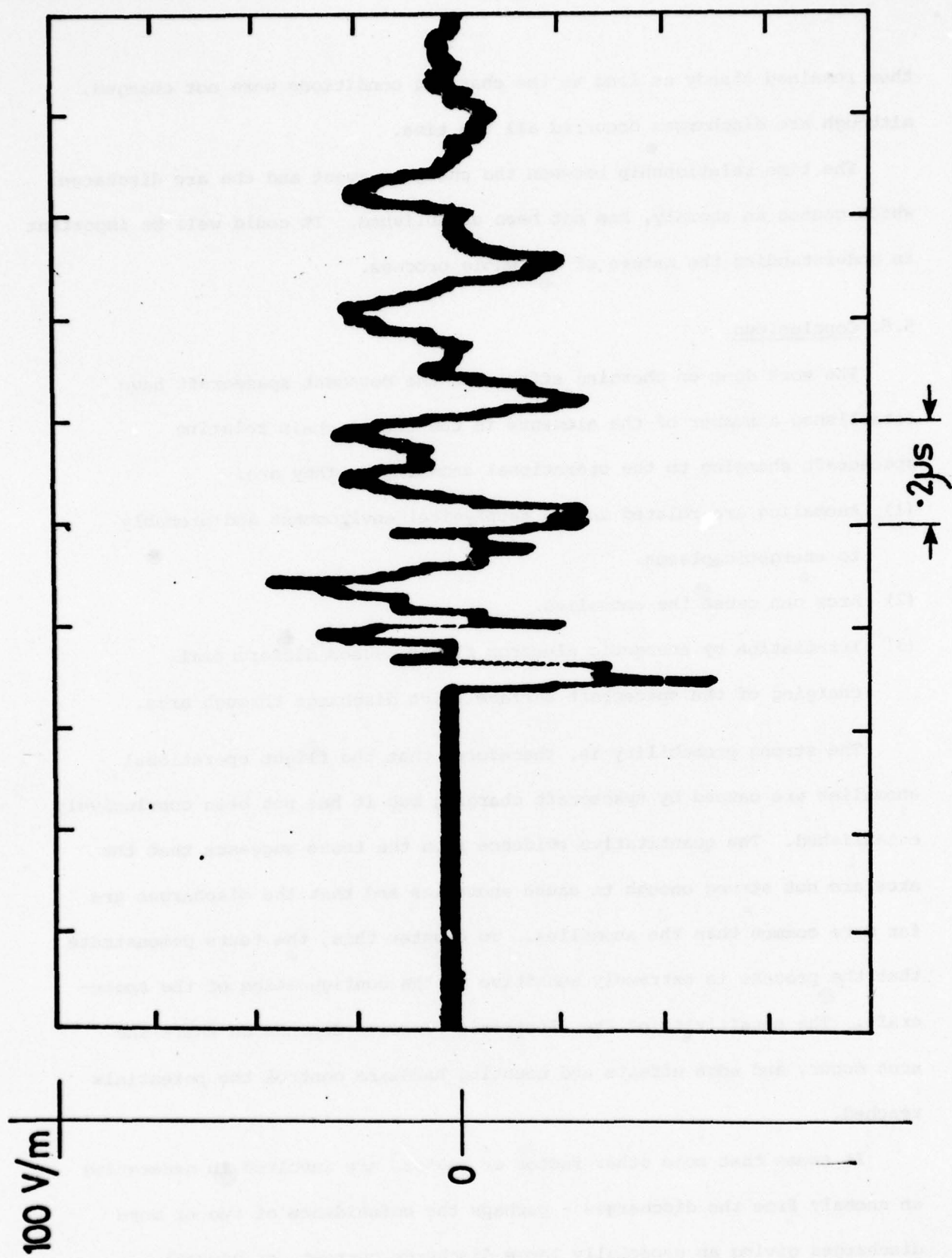
Figure 5.7   Radiated electric field of an arc discharge.

variations in the plasma environment. These factors will only be uncovered by monitoring the events on the spacecraft in flight because the conditions cannot be modelled closely enough in laboratory tests.

We therefore recommend that geosynchronous spacecraft, liable to be subjected to charging and especially differential charging, carry sensors to monitor the energetic electron fluxes and the occurrence of discharge currents in the spacecraft structure.

6. ACTIVE EXPERIMENTS

6.1. Probe Bias Control

Measurements of the thermal plasma, must be made close to 'space potential'. This normally requires sweeping or stepping a sensor voltage bias in order to overcome the spacecraft floating potential. Unpredictability of the latter leads to inefficient operation of Langmuir probes, retarding potential analysers and ion mass spectrometers. The automatic detection of plasma potential with servo-control of sensor voltage can be a solution to the problem. Both Wrenn and Blades[79] and Michau[55] report on systems developed for this purpose. A similar result can be achieved via a ground link with the on-line computing and command capabilities of GEOS.[45]

6.2. Active Control of Spacecraft Potential

Changing the voltage of any exposed surface can change the spacecraft potential and redistribute charge but this only serves to degrade the reference and increase sheath complexity. A real modification to the current balance can be achieved with electron or ion emitters and it is feasible to reduce the floating potential in this way.[74] Simple electron cathodes were first used by Storey[7] on the FR1 satellite and a more sophisticated electron gun was developed for rocket payloads by the University of Birmingham.[61] More recently a group at the European Space Technology Centre at Noordwijk have flown an electron gun on ISEE-1.[31] The technique is particularly relevant to satellite operation in hot plasmas because it provides a method of preventing large negative potentials; in addition to eclipse situations in the Earth's magnetosphere it might find application on spacecraft sensing the magnetospheres of Jupiter and Saturn where photoemission fluxes are much reduced. In a series of papers[34-38]

Grard has shown the merits of electron emitters in space and advocated the deployment of field emission electrodes in order to accomplish the desired limitation in charging. Such emitters could clamp the spacecraft potential near -300v or less, and have the advantage of requiring no power and being insensitive to ambient conditions.

Low energy particle experimenters have tended to resist the inclusion of active spacecraft potential devices in the fear that their detected fluxes will be contaminated by the emitted electrons. The truth is that the fluxes are, in any case, distorted by charging and the control device should be considered as a diagnostic aid. The decision to reject such a system for the Galileo Orbiter appears to be short-sighted.

The local plasma environment can also be modified by RF transmitters and the active wave experiments on GEOS[25] and ISEE-1[40] do provide an opportunity to study the observed effects on plasma measurements.

6.3. Electron and Ion Accelerators

Spacecraft charging is a by-product of active experiments in space plasmas which use particle accelerators. Emission of high-voltage, high-current pulses of electrons would cause the spacecraft to charge up to the accelerator potential, seriously reducing the particle ejection, if there were no neutralising return current from the ionosphere. The ARAKS project[24], which pioneered much rocket accelerator technology, used a caesium plasma source to improve neutralisation but, as it turned out, it was not a simple matter to determine the vehicle potential[16]; clearly the current balance involved complex plasma phenomena. In 1976 the NRDE group launched a Polar 5 rocket with an electron accelerator on a daughter payload; the latter charged to several hundred volts in spite of large-area 'wings'

deployed to collect current from the ionosphere.[42] They showed that the neutralising current returns preferentially from the direction of the beam, with beam-plasma interactions apparently producing the additional electrons to make up this current.

Better diagnostic instrumentation is the key to understanding this aspect of accelerator experiments and to this end Dr. Wilhelm of MPI Lindau and Dr. Beghin of CRPE Orlean lead teams of investigators utilising electron and ion accelerators on Spacelab Mission One.[17]

6.4. Ion Thrusters

The design of electric propulsion systems requires technologies closely related to those of spacecraft-potential control devices. In Europe, the initially wide-ranging development work has progressively been narrowed down with a view to achieving the first realistic application to North-South Station keeping. Of the four technological approaches subsequently brought to an advanced state of development (caesium contact and bombardment in France, mercury bombardment in the UK and mercury radio frequency ionisation (RIT) in Germany), only the German programme is now being pursued intensively.[58] In addition field-emission, electrostatic ion engines are now being studied.[59]

The UK T5[64] and German RIT 10[54] thrusters have been extensively described in the literature. As part of this programme long-life, highly efficient, hollow cathode neutralisers were developed to emit electron current; they could find application in spacecraft potential control.

One result of the programme is the existence of a number of groups within Europe with good facilities and the experimental and theoretical skills for tackling problems in fields related to spacecraft charging.

7. SUPPORTING STUDIES

7.1. Theoretical

Photoelectron emission from a sunlit spacecraft, outside the plasma-sphere, is normally the dominant current component. The spacecraft potential goes positive until the number of escaping photoelectrons balances the incoming electron current; emitted photoelectrons with energies less than the floating potential, form an asymmetric charge sheath around the spacecraft.[33][77] This photoelectron cloud has a maximum density on the sunward side. The potential distribution is asymmetric and modifies the trajectories of low energy particles in the neighbourhood of the space-craft.[72] Since these perturbations affect the response of low energy plasma and electric field detectors, some effort has been expended in modelling the photoelectron sheath to assess magnitude of the change. Various aspects of this problem have been treated for the GEOS[23][26][73] and HELIOS[41][51] satellites but the results could well be applied to other spacecraft in different situations.

Knott tackled the problem of a satellite in eclipse[49] and demonstrated the important role of secondary emission, which could also be significant at other times.[32]

The general problem of mapping electrostatic fields has been pursued in other areas of plasma research. For example, the Culham Laboratory have a great deal of experience with numerical computations of fields as part of their fusion programme.[39][75][76]

NASA have sponsored a charging analyser computer programme NASCAP which is a powerful tool for dynamically modelling the electrostatic charge and potential on and near a complex spacecraft; Mr. J. Reddy at ESTeC is currently engaged in obtaining a working version of the package.

7.2. <u>Laboratory</u>

Laboratory studies specifically conducted for simulation of spacecraft charging have been described in Section 5; these have been supported by irradiation tests of sub-systems such as thermal blankets, VHF shields,[11] solar array elements[8], OSR's[12] and large area samples of insulating surfaces used on ESA spacecraft.[19][63] In general, these tests have proved valuable for estimating the extent of particular charging hazards and the selection of suitable materials. Plasma chambers have been used quite extensively to test flight experiments and investigate associated problems.[48][60]

The surface physics group at ESTeC have made measurements of photo-emission and secondary emission yields of space materials[27][78] whilst many workers are involved with more general aspects of photoemission.[4]

Microscopic investigations of electrostatic discharge phenomena have been made by the ESA materials section. Electrostatic sparking is a hazard in many fields and a group at the Culham Laboratory has considerable experience with techniques for its analysis.[15]

7.3. <u>Materials</u>

Materials research is specifically excluded from this report but it must not be ignored because surface properties obviously play an important role in determining charging potentials. In particular, more work needs to be done on secondary emission characteristics; the maximum yields differ considerably[49][78] and suitable high yield materials should prove valuable in the prevention of serious charging.

To avoid differential charging a conductive coating is required for all exposed surfaces. ESA has demonstrated, with GEOS and ISEE, that

suitable conducting paints, coatings for solar cells and adhesives can be obtained[10][13] but less expensive solutions are needed. To this end new solar array materials are being developed[70] to meet the challenge presented by the proposed large solar power satellites.

8.   EUROPEAN GROUPS, FACILITIES AND INSTRUMENTATION

The following listing identifies groups whose work relates to some aspect of spacecraft charging. In each case a tabulation gives a brief outline of the nature of their work and the types of facilities and instrumentation available.

8.1 France

GROUP: CRPE (CNET/CNRS)

ADDRESS: AVENUE DE LA RECHERCHE SCIENTIFIC

                LA SOURCE

                45045 ORLEANS CEDEX

PERSONNEL: ARNAL, BEGHIN, HANELIN, HENRY, PIRRE, STOREY.

WORK: Plasma environment (GEOS). Interaction of ion and electron beams with plasmas; control of spacecraft potential during active plasma experiments (Spacelab 1).

FACILITIES: Cylindrical plasma chamber 2m diameter, 3m long, pressure 10^{-6} torr. Plasmas with densities 10^3 to 10^6 cm^{-3}, temperatures 500°K to 3000°K can be produced and contained magnetically by permanent magnets on chamber walls. Overall uniform magnetic field between 0 and 2 gauss can be produced. Used for testing wave diagnostic instrumentation and low energy particle detectors (44).

INSTRUMENTS: RF Plasma Probes, electron emitters.

* * *

GROUP: ONERA/CERT/DERTS   (SEE ALSO ESA/EOPO)

ADDRESS: ·2 AV. EDOUARD BELIN,

                31055 TOULOUSE FRANCE.

PERSONNEL: BERRY, BOURRIEU, LEVY, MOTTET, PAILLOUS.

WORK: Charging and discharging in simulated geomagnetic substorm conditions of components and spacecraft, particularly Meteosat.

Techniques for reducing the effects.

FACILTIES: SIMLES Vacuum chamber is 6m diameter, 7m high and achieves 10^{-8} torr pressure. Contains spin table on gimballed mounting, thermal control from $100^{o}K$ to $460^{o}K$, solar simulation lamps and an electron beam used recently in irradiation tests on Meteosat.

INSTRUMENTS: Plasma diagnostics, discharge monitors.

* * *

GROUP: AEROSPACIALE (SNIAS)

ADDRESS: BD. DE MIDI, BP52, OG322, CANNES, FRANCE.

PERSONNEL: ANDRAU, BURLE, DECHEZELLES.

WORK: Influence of charging on spacecraft design, evaluation of charging effects on spacecraft performance.

* * *

GROUP: ESA/EOPO (SEE ALSO ONERA/CERT/DERTS)

ADDRESS: 18, AV. EDOUARD BELIN,

C.S. TOULOUSE, 31 FRANCE.

PERSONNEL: HOGE, LEVERINGTON, SERENE

WORK:' Investigation into cause of operation anomalies of Meteosat. Responsible, as spacecraft management, for initiating and supporting series of investigations at various institutions.

* * *

GROUP: CERGA/ONERA

ADDRESS: CERG - 8BD EMILE ZOLA, O6130 GRASSE, FRANCE.

ONERA - 29 AV. DE LA DIVISION LECLERC, 92320

CHATILLON S/BAGNEUX.

PERSONNEL BARLIER, BOUDON, JUILLERAT, MAINGUY, VILLAIN.

WORK: Theoretical studies of bodies charging up in plasmas. (46)

8.2 West Germany

GROUP: DFVLR, INST FUR RAUMSIMULATION.

ADDRESS: LINDER HOHE, 5 KOLN 90, WEST GERMANY.

PERSONNEL: FEIBIG, GORLER, KLEIN.

WORK: Experimental and theoretical studies of Electrostatic charging and discharging of S/C surface materials. Expt. simulations (in vacuum chamber) of geomagnetic substorm conditions with high energy electron beam.

FACILITIES: Vacuum chamber 2.5 m diameter achieves pressure 10^{-5} torr. Contains electron irradiation facility which produces one metre diameter, nearly uniform beam, current density $10nA/cm^2$ (82)

* * *

GROUP: IPW/FREIBURG

ADDRESS: HEIDENHOFSTR 8, 7800 FREIBURG, WEST GERMANY.

PERSONNEL: R. GRABOWSKI, W. KAMPA, R. KIST, G. SCHMIDTE, P. SEIDL.

WORK: Theoretical studies of plasma-body interactions, form of S/C sheaths. Sheath effects on RF probes, plasma double layers. Degradation of surfaces when exposed to the space environment, particles and EUV from sun.

FACILITIES: 2 vacuum chambers, one devoted to Plasma tests, the other to XUV spectroscopy. Ability to simulate the geostationary orbit plasma environment. The plasma tank is 2.5m in diameter and 5m long, capable of a vacuum of 10^{-7} Torr. A plasma beam is produced by a Kaufman source, with argon as the working gas. Electron densities of the order 5×10^5 cm^{-3} can be achieved. The chamber is surrounded by three sets of orthogonal Helmholtz coils to control the magnetic field within the chamber.

INSTRUMENTS: RF plasma probes, XUV spectrometers

GROUP: MPI LINDAU

ADDRESS: MPI, POSTFACH 20, D3411, KATLENBURG, LINDAU 3, WEST GERMANY.

PERSONNEL: AXFORD, ROSENBAUER, SCHWENN, VASYLIUNAS, WILKEN, IP, STUDEMANN, WILHELM.

WORK: Scatha project involvement. Theoretical investigations into problems of

spacecraft charging in Jovian Environment (Voyager, Galileo).

Effects of photoemission on low energy electron measurements.

FACILITIES: Laboratory calibration for particle detectors, plasma detectors,

Ion Mass spectrometers, Electron beam analyser.

* * *

GROUP: MPI GARCHING

ADDRESS: 8046 GARCHING, BEI MUNCHEN, WEST GERMANY.

PERSONNEL: BOSWELL, HAERENDEL, PASCHMANN.

WORK: Particle measurements. Theoretical work on the physics of non-

neutral plasmas, and active control of spacecraft potential

using ion beams.

FACILITIES: Particle detector calibration

INSTRUMENTS: Fast plasma probes (ISEE 2)

* * *

GROUP: TECHNISCHE HOCHSCHULE, DARMSTADT.

ADDRESS: KAROLINAPLATZ 5, D-6100 DARMSTADT, WEST GERMANY.

PERSONNEL: U. ISENSEE, H. MASSBERG, G. VOIGT.

WORK: Theoretical studies of plasma/spacecraft interactions.

* * *

8.3 Holland

GROUP: ESA/ESTEC

ADDRESS: DOMEINWEG, NOORDWIJK, HOLLAND

PERSONNEL: 1) Scientific - FEUERBACHER, GONFALONE, GRARD, JONES, KNOTT,

PEDERSEN, WILLIS.

2) Technical - BOGUS, BOSMA, DAUPHIN, FROGGATT, GUSTAFFSON, KALWEIT, LERADON, REDDY, ROBBEN, WEBB.

WORK: DC Electric field measurement, electron emitters.

Materials study (effects of long term irradiation photoemission, secondary emission, conductivities). Effects of discharges on electrical subsystems. In-orbit monitoring of discharges. Charging of objects by Solar Simulation and Electrical irradiation. Solar Array/Cell and conductive layer development. Management of ESA Space Projects.

FACILITIES: Vacuum and Environmental Test Chambers including

(1) Spherical Chamber for Thermal Vacuum Testing of 3m diameter. Solar Simulation to 1.35 Suns, and Vacuum down to 10^{-7} torr possible. Test spacecraft is fitted to Gimbal System which allows sophisticated 2-axis motion.

(2) Smaller chamber of 2m diameter, vacuum down to 10^{-7} torr. Solar Simulation equipment. Gimbals similar to (1).

(3) Thermal Chamber down to 10^{-7} torr pressure. 1.5m by 2m high. Temperature range 150 K to 400 K.

(4) Systems for measurement of Photoemission and Secondary Emission coefficients.

INSTRUMENTS: Electric Field Probes, Emitters, Transient Events Monitors.

* * *

8.4 Italy

GROUP: LABORATORIO DI RICERCA E TECNOLOGIA PER LO STUDIO DEL PLASMA NELLO SPAZIO

ADDRESS: VIA G. GALIEI, CASELLA POSTALE 27, 00044 FRASCATI.

PERSONNEL: EGIDI, DOBROWOLNY, MORENO.

WORK: Plasma environment

INSTRUMENTS: Solar wind particle analysers (ISEE 2)

8.5 Norway

GROUP: NORWEGIAN DEFENSE RESEARCH EST (NDRE)

ADDRESS: PO BOKS 25, K JELLER, NORWAY.

PERSONNEL: T. JACOBSEN, B. MAEHLUM

WORK: Electron acceleration experiments on sounding rockets, supra-

                thermal and energetic electron measurements from sounding rockets.

INSTRUMENTS: Electron accelerators, current collecting surfaces, retarding

                potential analysers, energetic particle detectors.

* * *

8.6 Sweden

GROUP: KGI (KIRUNA GEOPHYSICAL INSTITUTE)

ADDRESS: S-98101 KIRUNA.

PERSONNEL: B. HULTQVIST, H. BORG, R. LUNDIN

WORK: Measurements of energetic electrons and positive ions in space,

                from sounding rockets in aurorae, low altitude satellites

                (ESRO-1, ESRO-4) and high altitude satellites (GEOS-1, GEOS-2).

                Measure fluxes responsible for charging and can detect high

                spacecraft potential.

INSTRUMENTS: Electrostatic analysers for electrons and protons 0.2 keV to 25 keV.

FACILITIES: Small vacuum chamber with extensive equipment for calibrating

                particle detectors.

* * *

8.7 Switzerland

GROUP: UNIVERSITY OF BERN

ADDRESS: PHYSIKALISCHES INSTITUT, UNIVERSITAT BERN.

                SIDLERSTRASSE 5, CH-3012 BERN.

PERSONNEL: BALSIGER, GEISS, YOUNG.

WORK: Plasma environment. Ion composition experiments which can measure

high floating potentials.

FACILITIES: Ion Beam Calibration System.

INSTRUMENTS: Ion Mass Spectrometer (GEOS, ISEE 1)

* * *

8.8 United Kingdom

GROUP: BAE (BRITISH AEROSPACE, FORMALLY BAC)

ADDRESS: FILTON HOUSE, BRISTOL BS99 7AB/GUNNELS WOOD RD.,

              STEVENAGE, HERTS.

PERSONNEL: C. FRANCIS, R.M. JENKINS, R. ROSENBERG.

WORK: Interested in status of spacecraft charging investigations with

              particular relevance to spacecraft design. Participated in

              development of ground techniques for GEOS satellites, and design

              of the ESA OTS satellite.

FACILITIES: Environmental testing.

* * *

GROUP: CULHAM LABORATORY

ADDRESS: ABINGDON OXON OX14 3DB ENGLAND

PERSONNEL: BUTTERWORTH, HARBOUR, THOMAS.

WORK: Ion Thruster Development. Electrostatic Field Analysis

              Discharge Detection.

* * *

GROUP: ERA

ADDRESS: CLEEVE ROAD, LEATHERHEAD, SURREY.   ENGLAND.

PERSONNEL: D.K. DAVIES.

WORK: Experimental/Theoretical Studies of Charging + Discharging

              Mechanisms of Insulators and Dielectrics.

GROUP: RAE FARNBOROUGH (ROYAL AIRCRAFT ESTABLISHMENT)

ADDRESS: SPACE DEPT, Q134 BUILDING, RAE, FARNBORUGH, HANTS. ENGLAND.

PERSONNEL: A. DOLLERY, D.G. FEARN, A. ROBBINS.

WORK: Investigations into the anomalies on SKYNET and METEOSAT.

Ion Thruster Development experience.

FACILITIES: The Vacuum Chambers at the Royal Aircraft Establishment were orignally used for Ion Thruster Development. The largest of the chambers is 3.5 m long and 1.5 m in diameter, and can be operated at pressures below 10^{-6} Torr. A smaller chamber is 1.8 m long by 0.9 m diameter and can be operated at similar pressures. In addition, there are two solar simulation facilities, the larger is 2.5 m in diameter, nearly 10 m long, and will pump down to 10^{-6} Torr. Six 30 KW carbon arc lamps are fitted at one end of the chamber which will allow illumination of area up to 2.5 m in diameter to the power of 1.5 suns. The test spacecraft is mounted on a remotely controlled 2-axis attitude system so that the illumination angles can be altered at will. The second chamber is 3 m in diameter, can be operated down to 10^{-6} Torr, and will maintain temperatures in the range -50 deg. C to +90 deg. C.

* * *

GROUP: SRC APPLETON LABORATORY.

ADDRESS: SLOUGH, ENGLAND.

PERSONNEL: BRYANT, EDWARDS, HALL.

WORK: Plasma Environment. Measurements of energetic electrons and positive ions in aurorae from sounding rockets. Development of Firewheel sub-satellite.

FACILITIES: Particle Detector Calibration.

INSTRUMENTS: Electrostatic Analysers, 200 eV - 20 keV.

* * *

GROUP: UCL/MULLARD SPACE SCIENCE LABORATORY.

ADDRESS: HOLMBURY ST. MARY, DORKING. SURREY.   ENGLAND.

PERSONNEL: J. JOHNSON, A.D. JOHNSTONE, K. NORMAN, G.L. WRENN.

WORK: Plasma Environment, Study of Thermal and Suprathermal Particles

                from rockets and satellites (Ariel 1, ESRO 1, ESRO 4, GEOS, OGO-5

                Firewheel).

FACILITIES: Small calibration chamber for particle Detectors.

INSTRUMENTS: R.P.A.'s and Electrostatic Analysers (< 1 keV)

* * *

8.9 Assessment of Research Groups

Within Europe there is little duplication of research effort and there-
fore no need to assign priority to the capabilities of different groups.
What should be discussed is the level of interest in spacecraft charging
per se, as contrasted with research carried out for another purpose which
nevertheless has relevance to spacecraft charging.

There are two main centres for work on charging per se. At ESTEC,
Noordwijk, research is carried out into many aspects of spacecraft charging;
on materials, on the spacecraft current balance, on the plasma environment
and the effect on spacecraft performance. The advice of the several groups
involved is available to all ESA projects. The second effort centres on a
particular ESA project, Meteosat, which since it was launched has only suffered
from one problem - differential charging. Since then a systematic investiga-
tion into the problem has been instigated by the Earth Observation Programme
Office of ESA in Toulouse with the assistance of ONERA, Toulouse, RAE Farn-
borough and the spacecraft main contractors SNIAS, Cannes.

The work in almost all the other institutions referred to, is conducted
primarily for basic scientific research.

It is worth comparing here the properties of the four principal vacuum
chambers. Two of them are vacuum chambers with electron irradiation facili-
ties - SIMLES chamber in Toulouse and the substorm simulation chamber at
DFVLR, Koln. The electron irradiation facility is an electron beam, fired
through an Aluminium diffusing screen. The SIMLES chamber is very large and
can hold a large spacecraft, while the DFVLR chamber is more modest and
designed for the irradiation of components rather than spacecraft.

The other two chambers, at Orleans and Freiburg are very similar in size
and capability. Both produce a plasma, unlike the first two mentioned, in
which instruments and components can be immersed. In the Freiburg chamber
the plasma flows past the instruments with the velocity of an ionospheric
satellite, 8 km/s. They do not contain irradiation facilities although they
could easily be added.

9. CONCLUSIONS AND RECOMMENDATIONS

The main conclusion of this study is that there is a great deal of important research being done in Europe on the problem of spacecraft charging. This is illustrated by the length of the bibliography. From the results of this work a number of lessons have been learned but there are also some problems that need to be resolved. In this chapter we try to summarise the lessons, point out the problems and recommend ways to make further progress.

The first lesson is that no-one, whether spacecraft engineer or scientist, can ignore spacecraft charging. It is not just a problem to be considered by those interested in the ambient plasma; it can affect the data collection or operations of any spacecraft in geosynchronous orbit. While there is little doubt that charging, and subsequent arc discharges, are responsible for operational anomalies the quantitative relationship between the ambient plasma parameters, spacecraft potentials, the magnitude of the arc electric fields, and their effect on spacecraft electronics, is not well-established. There could be important factors which have not yet been recognised. Investigation into the mechanisms of charging and discharging should continue and we recommend or endorse the following specific actions or investigations:

(i) that GEOS-2 be moved to 0° longitude where it can record with some accuracy the ambient plasma conditions experienced by the Meteosat spacecraft.

(ii) that the second flight model of Meteosat carry sensors to record the occurrence of arc discharges and monitor the ambient energetic electron fluxes.

(iii) that joint experimenters' workshops be held to analyse in detail events occurring during close encounters between the SCATHA spacecraft and GEOS-2, and SCATHA and Meteosat.

(iv) that specific attention be given to the possibility of delays between

plasma events which charge the spacecraft to high potentials and the arcing which causes anomalies.

(v) that the role of secondary emission in controlling the potential of electron irradiated surfaces be investigated.

The second lesson is that differential charging, the real cause of arcing, can be effectively eliminated by suitable techniques (sec. 4) in design, and construction and that these techniques will not degrade other aspects of spacecraft performance. This has been demonstrated very clearly by the GEOS and ISEE-B spacecraft. These techniques are said to be expensive but there does not seem to be any reason why this should necessarily remain the case. We recommend that *work should be done to lower the cost and improve the effectiveness of the techniques of electrostatic cleanliness, so that they can be included as a matter of standard practice on spacecraft going outside the plasmasphere.*

A conducting outer surface prevents differential charging but does not prevent the spacecraft reaching high negative potentials under some plasma conditions. There are apparently differences between the susceptibility of spacecraft to charging of this type. GEOS for example has only rarely reached potentials of more than 100 volts, even in eclipse. The secondary emission coefficient of the surface material may be important in this respect. The discovery of a material with a yield greater than unity for incident keV electrons would be particularly important. We recommend *that a search for materials with a high secondary electron yield be made.* The only certain way to control the potential of a spacecraft is by controlled emission of electrons. This technique is still being questioned where it might be most valuable, — on scientific satellites to measure the ambient plasma, because the emitted electrons may create a background for the measurement of natural electrons. There are many uncertainties about the trajectories of all photo- and secondary electrons, originating from the spacecraft, to form the spacecraft sheath and helping to set its potential. We recommend *controlled experiments*

to investigate these questions, particularly on the ISEE-B spacecraft.

The most novel approach to active potential control is the field-emission emitter proposed by Grard [34]. The device requires no power and can be combined with some basic diagnostic measurements. We recommend that *this technique be investigated further and if possible tested on a spacecraft.*

The work being carried out in Europe cannot be considered to be a coordinated attack on the problems of spacecraft charging. A group at ESTEC under Mr C. Kalweit has been established to coordinate ESA activities but there are many groups outside ESA capable of making significant contributions. We feel that it is perhaps an appropriate time to recommend *a European conference on spacecraft charging to be organised with contributions solicited from the groups identified in this report.* Such a meeting could be an effective means of stimulating cooperation between the many different types of institution interested in this topic and promoting a concerted research programme.

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